UNIVERSITY OF ILLINOIS BULLETIN
ISSUED TWICE A WEEK
Vol. XXXV September 3, 1937 No. 2
[Entered as second-class matter December 11, 1912, at the post office at Urbana, Illinois, under the Act of August 24, 1912. Acceptance for mailing at the special rate of postage provided for in section 1103, Act of October 3, 1917, authorized July 31, 1918.]

RESISTANCE TO HEAT CHECKING OF CHILLED IRON CAR WHEELS, AND STRAINS DEVELOPED UNDER LONG-CONTINUED APPLICATIONS OF BRAKE SHOES

A REPORT OF AN INVESTIGATION

CONDUCTED BY

THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

IN COÖPERATION WITH

THE ASSOCIATION OF MANUFACTURERS
OF CHILLED CAR WHEELS

BY

EDWARD C. SCHMIDT

AND

HERMAN J. SCHRADER

BULLETIN No. 298
ENGINEERING EXPERIMENT STATION
PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

PRICE: FIFTY-FIVE CENTS

THE Engineering Experiment Station was established by act of the Board of Trustees of the University of Illinois on December 8, 1903. It is the purpose of the Station to conduct investigations and make studies of importance to the engineering, manufacturing, railway, mining, and other industrial interests of the State.

The management of the Engineering Experiment Station is vested in an Executive Staff composed of the Director and his Assistant, the Heads of the several Departments in the College of Engineering, and the Professor of Chemical Engineering. This Staff is responsible for the establishment of general policies governing the work of the Station, including the approval of material for publication. All members of the teaching staff of the College are encouraged to engage in scientific research, either directly or in coöperation with the Research Corps, composed of full-time research assistants, research graduate assistants, and special investigators.

To render the results of its scientific investigations available to the public, the Engineering Experiment Station publishes and distributes a series of bulletins. Occasionally it publishes circulars of timely interest, presenting information of importance, compiled from various sources which may not readily be accessible to the clientele of the Station, and reprints of articles appearing in the technical press written by members of the staff and others.

The volume and number at the top of the front cover page are merely arbitrary numbers and refer to the general publications of the University. *Either above the title or below the seal* is given the number of the Engineering Experiment Station bulletin, circular, or reprint which should be used in referring to these publications.

For copies of publications or for other information address

THE ENGINEERING EXPERIMENT STATION,
UNIVERSITY OF ILLINOIS,
URBANA, ILLINOIS

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No. 298 SEPTEMBER, 1937

RESISTANCE TO HEAT CHECKING OF CHILLED IRON CAR WHEELS, AND STRAINS DEVELOPED UNDER LONG-CONTINUED APPLICATIONS OF BRAKE SHOES

A REPORT OF AN INVESTIGATION

CONDUCTED BY

THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

IN COÖPERATION WITH

THE ASSOCIATION OF MANUFACTURERS
OF CHILLED CAR WHEELS

BY

EDWARD C. SCHMIDT
PROFESSOR OF RAILWAY ENGINEERING

AND

HERMAN J. SCHRADER
ASSISTANT PROFESSOR OF RAILWAY MECHANICAL ENGINEERING

INDUSTRIAL ARTS
Not to be taken from this office
FEB 7 1938
Received
Indexed
Card taken out
Written
Compared

ENGINEERING EXPERIMENT STATION
PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

4000—8-37—12680

UNIVERSITY
OF ILLINOIS
PRESS

CONTENTS

	PAGE
I. Introduction	7
1. Purpose of Investigation	7
2. Test Procedure and General Results	7
3. Acknowledgments	8
II. Wheels, Brake Shoes, and Testing Equipment	9
4. Wheels	9
5. Brake Shoes	9
6. Testing Equipment	12
III. Test Program and Procedure	15
7. Test Program	15
8. General Test Procedure	17
9. Procedure for Measurement of Temperature and Strains	19
IV. Results of Tests	20
10. Results of Tread Endurance Determinations	20
11. Measurements of Temperatures and Strains	33
12. Supplementary Temperature Determinations	45
V. Summary and Conclusions	47
13. Tread Endurance	47
14. Strains Developed	48
Appendix	49

INDUSTRIAL ARTS
Not to be taken from this office
REF
Received
Written

LIST OF FIGURES

NO.		PAGE
1.	Location of Gage Lines and Thermocouples on Test Wheel No. 1	13
2.	Application of Thermocouples and Slip Ring Connections	14
3.	Arrangement of Recording Table	15
4.	Condition of Tread of Wheel No. 1 After Each Series of Tests	20
5.	Condition of Treads of Wheels Nos. 2, 3, 5, 6, and 7 After Tests	21
6.	Condition of Tread of Wheel No. 1 After Tests, Series 3501-30 and 3502-30	22
7.	Condition of Tread of Wheel No. 1 After Tests, Series 3503-15 and 3503-30	23
8.	Condition of Tread of Wheel No. 1 After Applications Nos. 5, 10, 15, 20, 25, and 30 of the 3504 Test Series, After Polishing Tread	24–25
9.	Condition of Tread of Wheel No. 2 After Applications Nos. 5, 10, 15, 20, 25, and 30 of the 3505 Test Series, After Polishing Tread	26–27
10.	Condition of Tread of Wheel No. 3 After Applications Nos. 5, 10, 15, 20, 25, and 30 of the 3506 Test Series, After Polishing Tread	28–29
11.	Condition of Tread of Wheel No. 5 After Applications Nos. 5, 10, 15, and 20 of the 3509 Test Series, After Polishing Tread	30
12.	Condition of Tread of Wheel No. 6 After Applications Nos. 5, 10, 15, and 20 of the 3510 Test Series, After Polishing Tread	31
13.	Condition of Tread of Wheel No. 7 After Applications Nos. 5, 10, 15, and 20 of the 3511 Test Series, After Polishing Tread	32
14.	Results of Tests 3500-17 and 3500-18	38
15.	Results of Tests 3501-22 and 3501-25	39
16.	Results of Tests 3502-27 and 3502-28	40
17.	Results of Tests 3503-5 and 3503-17	41
18.	Results of Tests 3504-1 and 3504-5	42
19.	Results of Tests 3504-6 and 3504-16	43
20.	Temperature, Work, Friction, and Tangential Unit Strain Developed in Rim of Wheel No. 1 During Test 3503-25	44
21.	Nature, Location, and Magnitude of Radial Surface Strains Induced in Wheel No. 1 During Test 3503-17, Which Was Run at 25 Miles per Hour With Shoe Applied at 3000 Pounds Pressure for 48 Minutes	45
22.	Temperature of Thermocouples Nos. 1 to 7 for Tests 3501-2 and 3502-30, Wheel Running at 25 Miles per Hour While Cooling	46
23.	Thermal Expansion of Specimens Cut From Wheel No. 1	49
24.	Stress–Strain Diagrams for Tension and Compression Tests, Wheel No. 1	50

LIST OF TABLES

NO.		PAGE
1.	General Information Regarding Test Wheels	10
2.	Chemical Composition of Test Wheels	10
3.	Diameter and Tread Hardness of Wheels Before and After Tests	10
4.	Brinell Hardness, Thickness, and Weight of Brake Shoes Before and After Tests	11
5.	Program of Tests	16
6.	Record of Cracks Longer Than 2¾ Inches on Treads of Wheels Nos. 2, 3, 5, 6, and 7	21
7.	General Results	34
8.	Railway Operating Conditions Similar to Conditions Under Which Tests Were Made	34
9.	Summary of Results of Strain Tests	35

RESISTANCE TO HEAT CHECKING OF CHILLED IRON CAR WHEELS, AND STRAINS DEVELOPED UNDER LONG-CONTINUED APPLICATIONS OF BRAKE SHOES

I. Introduction

1. *Purpose of Investigation.*—The investigation whose results are presented in this bulletin was undertaken primarily to study the effects of long-continued applications of brakes upon the treads of chilled iron car wheels, particularly as regards the development of heat checks, cracks, and brake burns. The secondary purpose was to determine the strains and the stresses set up in a wheel under such brake applications.

When brakes are applied to stop a train the duration of the application is short, although the brake shoe pressure may be high. When, however, the brakes are used to control the train's speed on a descending grade, the brakes may be kept applied for long periods, but under shoe pressures which are generally much lower than those employed in making a stop. In the latter instance the total energy dissipated by the brakes is generally much greater than in the former, and the resulting heat may damage the wheels.

2. *Test Procedure and General Results.*—In the investigation six chilled iron wheels were used, differing somewhat in weight, tread contour, composition, and manufacturing treatment. Wheel No. 1 was subjected to shoe pressures of 1000, 1500, 2000, 3000, and 4000 pounds, the other wheels to a pressure of 3000 pounds only. These six wheels were subjected to a total of 270 brake applications, most of them with the rim speed kept constant at 25 miles per hour, and the shoe applied continuously for 48 minutes. With only two exceptions, the applications at 4000 pounds shoe pressure were made at 15 miles per hour and lasted 80 minutes. Each of these combinations of speed and duration result in a travel of the test wheel tread equivalent to 20 miles. Wheel No. 1, which was tested throughout the entire pressure range, was subjected to 150 applications and was under brake shoe action for the equivalent of 2985 miles; wheels Nos. 2 and 3, to thirty applications and for 600 miles, each; and wheels Nos. 5, 6 and 7, to twenty applications and for 400 miles. The details of the test program are presented in Table 5. The results of the tests are set forth in detail in

Chapter IV, and it is sufficient, therefore, here to summarize them very briefly.

Applications at 1000, 1500, and 2000 pounds shoe pressure did not damage wheel No. 1 to any considerable extent; only a few heat checks and short cracks had developed upon the completion of the tests at these pressures. Pressures of 3000 pounds damaged not only the tread of wheel No. 1, but those of all the five other wheels, which had not been subjected to the preliminary tests at lower pressures. This pressure produced on all six wheels numerous cracks, many of them longer than 2¾ inches—the current condemning limit. The 4000-pound applications caused additional damage to wheel No. 1. No "comby" spots or "shell-outs" were produced on any of the wheels during the entire investigation.

Neglecting the effect of combined stresses, the maximum direct stress developed in wheel No. 1 occurred under 4000 pounds shoe pressure. This was a radial tensile stress on the outer surface of the plate near the hub, and amounted to 23 300 pounds. The stresses set up in directions at right angles to the wheel radii were insignificant in amount.

3. *Acknowledgments.*—This investigation was undertaken as one of the researches of the Engineering Experiment Station of the University of Illinois, in coöperation with the Association of Manufacturers of Chilled Car Wheels. The University and this Association shared the expense.

In accordance with the general practice of the Experiment Station in such researches, the scope of the tests and the general program were defined by an Advisory Committee, on which the Association was represented by Mr. F. K. Vial, Vice President, in charge of Research, and S. C. Massari, Metallurgist. About midway in the investigation Mr. Massari's place was taken by Mr. C. M. Stoner, Engineer of the Association. The Experiment Station's representatives on the committee were professors Edward C. Schmidt and Herman J. Schrader.

As stated, this research was part of the work of the Engineering Experiment Station of the University, of which Dean M. L. Enger is the Director. The conduct of the tests, the calculations and analysis of the data, and the preparation of the report were under the exclusive control of the Railway Engineering Department, which acted for the Station, and which assumes full responsibility.

Special acknowledgment is made of the assistance received from Mr. C. L. Thompson, formerly Associate in Ceramic Engineering, who

determined the coefficients of thermal expansion of the wheel material; and from Mr. R. L. Brown, Research Associate in Theoretical and Applied Mechanics, who established the relations between strain and stress for the wheel metal.

At the time this investigation was undertaken the Association of Manufacturers of Chilled Car Wheels entered into a similar agreement with the Department of Theoretical and Applied Mechanics of the University for an investigation of the stresses produced in chilled wheels under various conditions of loading. This research was carried on by Messrs. Richart, Brown, and Jones, and its results have been published in Bulletin No. 294 of the Engineering Experiment Station, which is entitled "Tests of Strength Properties of Chilled Car Wheels."

II. Wheels, Brake Shoes, and Testing Equipment

4. *Wheels.*—Six wheels were tested. Throughout this report they are designated as Nos. 1, 2, 3, 5, 6, and 7, respectively. They were furnished by the Association of Manufacturers of Chilled Car Wheels, and were made by the Griffin Wheel Company at one of its Chicago plants. They were all 33-inch chilled iron single-plate wheels of current standard design.

The nominal weight of wheels Nos. 3 and 6 was 750 pounds, of the others 700 pounds. They differed somewhat in manufacturing process and in chemical composition, as indicated in Tables 1 and 2. The tread of No. 7 had a straight taper of one in twenty; the tread and flange contour of all the others conformed to the current standard of the Association of American Railroads, as defined in the Wheel and Axle Manual, February, 1935, of its Mechanical Division, in Fig. 62, page 87. These contours were maintained throughout the tests.

Both at the beginning and at the end of the investigation the hardness of the wheel treads was determined, by means of a Shore scleroscope, at twenty points on each wheel. These determinations were made along four lines marked on the tread, parallel to the axle and 90 degrees apart, at five spots on each line. Table 3 shows the results of these measurements and also the sizes of the wheels before and after the tests.

5. *Brake Shoes.*—The brake shoes used during all tests were plain unflanged cast-iron shoes with chilled ends. They were obtained from the American Brake Shoe and Foundry Company, which designates them as "Special Chilled" shoes, style C-4, pattern No. C-40. This

TABLE 1
GENERAL INFORMATION REGARDING TEST WHEELS

Test Wheel No.	Manufacturer's Wheel No.	Nominal Weight lb.	Date of Casting	Ladle Treatment	Kind of Primary Pit	Time in Primary Pit hr.	Temperature at Transfer deg. F.
1	A23676	700	4-27-34	½ lb. S.M.*	Standard	68	1280
2	A23681	700	4-27-34	None	Standard	68	1280
3	697388	750	10-21-35	1½ lb. Chrome	Electric Oven	7½	1600†
5	697349	700	10-25-35	5 lb. Chrome	Electric Oven	7½	1600†
6	129174	750	9-20-35	¼ lb. Chrome	Oil Fired Oven	20	1360
7	A23719	700	4-27-34	None	Standard	68	1280

*S.M. consists of 47 to 54 per cent silicon, 20 to 25 per cent manganese, and 25 to 30 per cent iron.
†Wheels 3 and 5 were cooled in the electric oven at a rate of about 40 deg. F. per hour.

TABLE 2
CHEMICAL COMPOSITION OF TEST WHEELS

Wheel Number	Carbon			Manganese	Phosphorus	Sulphur	Silicon
	Graphitic	Combined	Total				
1	2.69	0.78	3.47	0.52	0.346	0.116	0.54
2	2.68	0.72	3.40	0.53	0.341	0.142	0.52
3	2.72	0.70	3.42	0.53	0.307	0.134	0.61
5	2.53	0.87	3.40	0.51	0.312	0.157	0.71
6	2.78	0.69	3.47	0.57	0.312	0.143	0.60
7	2.70	0.86	3.56	0.55	0.318	0.115	0.55

TABLE 3
DIAMETER AND TREAD HARDNESS OF WHEELS BEFORE AND AFTER TESTS

Wheel No.	Test Series Number	Circumference ft.		Diameter in.		Hardness by Shore Scleroscope					
						Before			After		
		Before	After	Before	After	Max.	Min.	Av.	Max.	Min.	Av.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1	3500	8.630	8.630	32.96	32.96	69	59	63.7	..	..	....
	3501	8.630	8.630	32.96	32.96	..	..	....	..	..	....
	3502	8.630	8.625	32.96	32.95	..	..	....	..	..	....
	3503	8.625	8.620	32.95	32.93	..	..	....	..	..	....
	3504	8.609	8.604	32.88	32.86	..	..	....	66	60	62.2
2	3505	8.609	8.609	32.88	32.88	65	55	60.2	73	59	66.3
3	3506	8.641	8.625	33.01	32.95	63	53	57.9	69.5	57	64.2
5	3509	8.609	8.604	32.88	32.86	62	47	55.0	68	58	62.6
6	3510	8.589	8.584	32.81	32.79	69	51.5	60.3	71	61	66.3
7	3511	8.591	8.589	32.82	32.81	69.5	62	65.3	71	61	65.1

TABLE 4
BRINELL HARDNESS, THICKNESS, AND WEIGHT OF BRAKE SHOES BEFORE AND AFTER TESTS

Shoe No.	Average Brinell Hardness of Shoe				Weight lb.		Average Thickness in.	
	Before		After					
	Chilled End	Body	Chilled End	Body	Before	After	Before	After
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
40	460	364	408	343	18.38	13.16	1.36	0.92
41	491	380	424	398	18.53	11.87	1.35	0.80
42	437	321	446	291	17.39	12.07	1.24	0.80
43	447	275	309	282	16.05	9.15	1.12	0.55
44	438	291	416	265	17.54	15.95	1.24	1.11
45	478	342	431	296	17.17	10.98	1.22	0.71
46	423	344	431	302	19.06	12.69	1.36	0.84
47	415	363	444	297	18.91	11.30	1.36	0.73
150	460	269	368	270	18.34	12.47	1.38	0.84
151	515	270	395	235	17.57	12.66	1.31	0.86
152	488	274	409	264	18.19	14.24	1.33	0.96
153	507	218	357	250	17.87	12.12	1.31	0.78
154	489	274	357	285	18.09	12.08	1.36	0.80
155	475	275	377	270	18.33	13.65	1.33	0.90
160	470	280	382	264	18.90	13.07	1.42	0.88
161	480	280	369	265	18.78	14.60	1.36	0.99
162	515	274	389	239	18.56	12.20	1.39	0.80
163	524	274	438	246	18.93	16.03	1.39	1.12
164	470	274	359	246	19.03	12.82	1.40	0.83
165	478	285	408	264	18.63	16.18	1.37	1.14
166	498	245	438	269	19.11	17.87	1.36	1.25

shoe is used chiefly on freight cars, and is fairly typical of the plain cast iron shoes which preponderate in freight service. They were received in two shipments, and were numbered, respectively, 40 to 49 and 150 to 169 inclusive.

From one to three sixteenths of an inch was ground from the face of each shoe to remove surface hardness, and to fit the shoe to the test wheel. Thus prepared, their hardness was measured, by means of a Brinell machine, at seven points on the contact face; and these measurements were repeated after the shoe was withdrawn from test service. The results appear in Table 4. The values given in columns 2 and 4 of this table are the averages of four determinations—two near each end of the shoe in the chilled material. The values in columns 3 and 5 are averages of three determinations made along the longitudinal center line of the shoe face—one at the middle, and one 2½ inches each way therefrom. Before and after its test service each shoe was weighed, and its thickness was measured at four points

—two on each side, one and one-half inches from the ends. The weights are given in columns 6 and 7 in Table 4, and the average thickness in columns 8 and 9.

6. *Testing Equipment.*—The tests were made by means of the brake-shoe testing machine of the Railway Engineering Department, which, in all fundamental features, is like the original machine of the former Master Car Builders' Association.* It consists essentially of a car wheel keyed to a main shaft which carries also a heavy flywheel. This system may be rotated at any desired speed by means of a steam engine which drives the shaft through a pulley and a clutch.

The shoe to be tested is held in a brake-shoe head of special design and is suspended above the wheel from one of a pair of levers by means of which the shoe may be applied to the wheel with any desired pressure up to a maximum of 20 000 pounds. The tangential pull of the shoe which is developed when it is thus applied to the rotating wheel is transmitted by a horizontal yoke to a dynamometer which makes a continuous graphical record of the pull. In making constant-speed tests such as are here under discussion, the machine is brought up to the desired speed, the brake shoe is applied, and the wheel is constantly driven at the desired speed against the frictional resistance of the applied shoe.

Strains produced in the wheel due to the heat generated by the brake application were measured by means of a Berry strain gage on wheel No. 1 only. The gage holes for the radial strains were two inches apart and were located on two radii. Along these same radii, but at right angles to them, were located the holes for the measurement of "tangential" strains. For the measurement of strains in the plate of the wheel there were, on both its outer and inner faces, eight gage lines for radial strains and eight for tangential strains. For the measurement of tangential strains in the rim of the wheel there were on each face four additional gage lines. All gage lines are shown in Fig. 1. They are designated throughout the report by their respective numbers, accompanied by either the letter R or T, depending upon whether their direction was radial or tangential; and also by either the letter O or I, depending on whether they were located upon the outer or the inner wheel face.

Since for each strain measurement the concurrent temperature of

*The original machine is described in the Proceedings of this Association, in Vol. 28, 1894, pages 154-161. The University of Illinois machine is illustrated and described in Bulletins 135 and 257 of the Engineering Experiment Station.

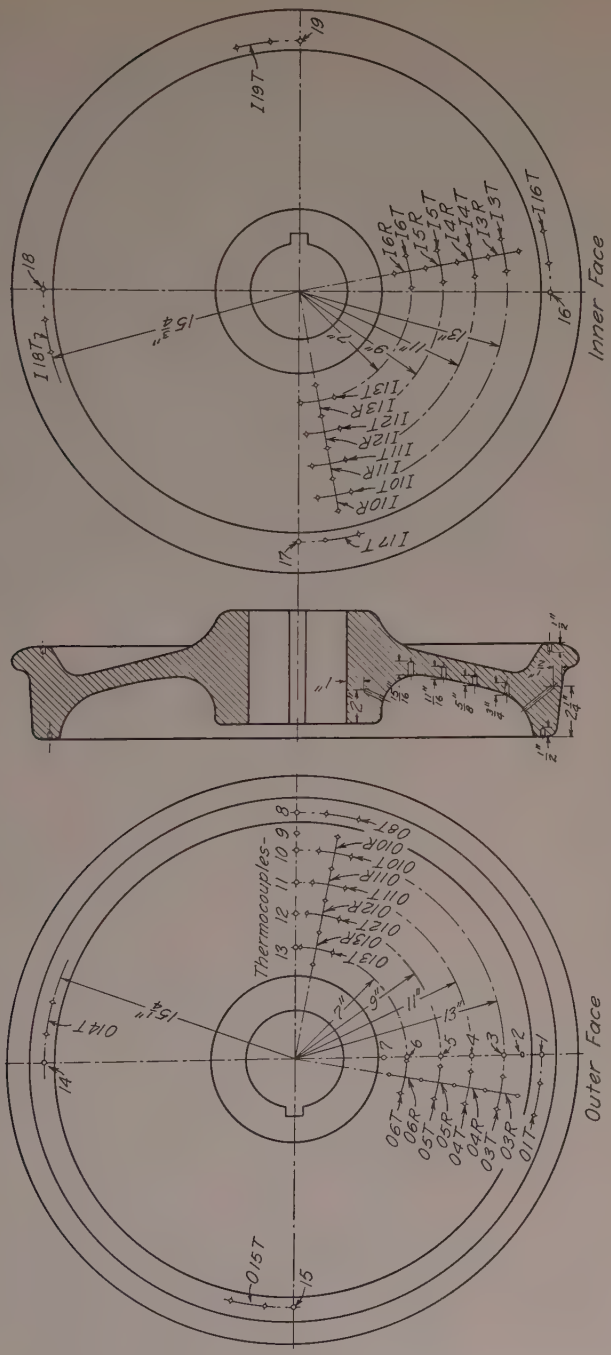


FIG. 1. LOCATION OF GAGE LINES AND THERMOCOUPLES ON TEST WHEEL NO. 1

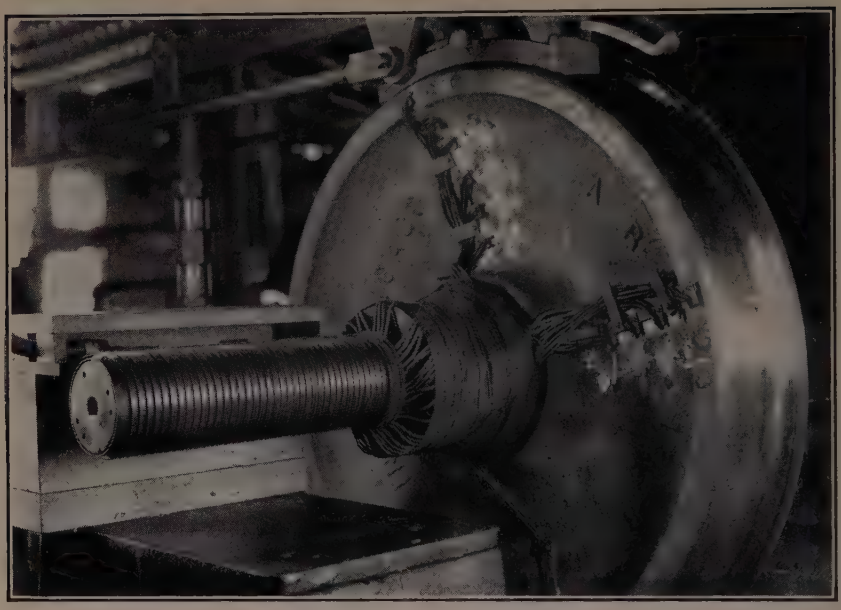


FIG. 2. APPLICATION OF THERMOCOUPLES AND SLIP RING CONNECTIONS

the material is needed in order to convert strain into stress, thermocouples were inserted in the wheel adjacent to all gage lines. Their location is shown in Fig. 1. For the gage lines in the plate of the wheel eight couples were there inserted in its center, being located on two radii closely adjacent to the gage line axes. These couples are numbered 3, 4, 5, 6 and 10, 11, 12, 13. They served for the plate stress determinations on both wheel faces. In the rim of the wheel, on each face, four additional thermocouples were placed adjacent to the corresponding gage lines. Couple No. 7 was placed within the hub, as shown in the figure; and on the same radii as the plate couples were two more, inserted from the outer face to within one-half inch of the surface of the wheel tread.

All thermocouples were made of 22-gage copper and constantan wire. Each was connected to a pair of slip-rings carried on an extension of the shaft of the testing machine; and from them the connections were extended to the switch box, the cold junction, and the potentiometer. Figure 2 shows the attachment of the couples to the wheel, and their connection to the slip-rings. The recording table arrangements are shown in Fig. 3.

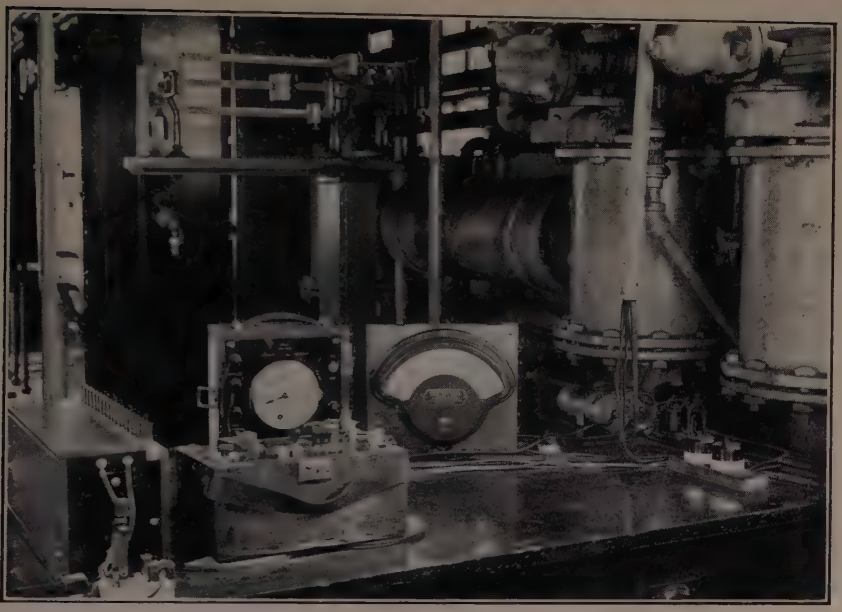


FIG. 3. ARRANGEMENT OF RECORDING TABLE

III. TEST PROGRAM AND PROCEDURE

As stated in the introduction, the main purpose of the investigation was to study the resistance of the wheel treads to long-continued brake applications; and the secondary purpose, to determine the strains developed by such applications. The tread endurance determinations were made on all six wheels. The strain measurements, however, were made on wheel No. 1 only, and during only a portion of the regular runs made with that wheel.

Since at the outset there was no information as to the shoe pressure which would be likely to damage the tread, the applications for the first wheel tested (No. 1) were begun at the low pressure of 1000 pounds, and the pressures were successively increased to 1500, 2000, 3000, and 4000 pounds. The tests with wheel No. 1 having shown that repeated applications at less than 3000 pounds caused very slight damage, the five other wheels were subjected to a shoe pressure of 3000 pounds only.

7. *Test Program.*—The general test program is shown in Table 5, which indicates for each wheel the various combinations of shoe pres-

TABLE 5
PROGRAM OF TESTS

Series No.	Test Wheel No.	Shoe No.	Brake Shoe Pressure lb.	Wheel Rim Speed m.p.h.	Application No.	Number of Applications	Duration of Each Application		Miles Brake Applied
							min.	miles	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
3500	1	40	1000	25	1-30	30	48	20	600
3501	1	40	1500	25	1-30	30	48	20	600
3502	1	41	2000	25	1-30	30	48	20	600
3503	1	42	3000	25	1-13	13	48	20	260
	1	43	3000	25	14-27	14	48	20	280
	1	44	3000	25	28-30	3	48	20	60
3504	1	45	4000	15	1-10	10	80*	20*	192.5
	1	46	4000	15	11-20	10	80*	20*	192.5
	1	47	4000	15	21-30	10	80	20	200
			Total miles brake applied to Wheel No. 1						2985.0
3505	2	150	3000	25	1-13	13	48	20	260
	2	151	3000	25	14-23	10	48	20	200
	2	152	3000	25	24-30	7	48	20	140
			Total miles brake applied to Wheel No. 2						600
3506	3	153	3000	25	1-12	12	48	20	240
	3	154	3000	25	13-21	9	48	20	180
	3	155	3000	25	22-30	9	48	20	180
			Total miles brake applied to Wheel No. 3						600
3509	5	160	3000	25	1-13	13	48	20	260
	5	161	3000	25	14-20	7	48	20	140
			Total miles brake applied to Wheel No. 5						400
3510	6	162	3000	25	1-15	15	48	20	300
	6	163	3000	25	16-20	5	48	20	100
			Total miles brake applied to Wheel No. 6						400
3511	7	164	3000	25	1-14	14	48	20	280
	7	165	3000	25	15-18	4	48	20	80
	7	166	3000	25	19-20	2	48	20	40
			Total miles brake applied to Wheel No. 7						400

*Tests 3504-6 and 16 were special tests of 50 minutes duration and equivalent to a 12.5-mile run.

sure and speed to which it was subjected, the number of applications at each combination, their duration, and their mileage. The tests were made in numbered series, the series changing with any change in the wheel used or in the shoe pressure. Each application constituted a test, and was given its own number within the series. For example, the fourth of the thirty tests run at 1000 pounds pressure, 25 miles per hour, and 48 minutes duration, is designated as test No. 3500-4.

During the investigation the six wheels were given a total of 270 brake applications, of which 240 were at 25 miles per hour and lasted for 48 minutes. Under these circumstances the wheel tread travel is equivalent to 20 miles actual travel in service. Twenty miles was somewhat arbitrarily chosen as representing conditions which may prevail in service in controlling trains on long grades. The remaining 30 applications were made at 15 miles per hour. These were all tests on wheel No. 1, run at 4000 pounds shoe pressure—28 of them with a duration of 80 minutes, again equivalent to 20 miles; and 2 special tests of 50 minutes duration, equivalent to a run of 12.5 miles. As indicated in Table 5, wheel No. 1 was subjected, all told, to 150 applications, for which the accumulated mileage was 2985. Wheels Nos. 2 and 3 were each given 30 applications, all at 3000 pounds shoe pressure, representing 600 miles; while wheels Nos. 5, 6 and 7 were subjected, under 3000 pounds pressure, to 20 applications each, equivalent to 400 miles.

8. *General Test Procedure.*—In preparation for the early tests on wheel No. 1 the wheel was mounted on the testing machine shaft and its tread there ground to as true a circle as then seemed necessary; that is, to a diameter variation of not over 0.001 of an inch. The weights on the lever system were then adjusted to produce the desired shoe pressure. In tests of this wheel at 1000 and 1500 pounds (series 3500 and 3501) difficulty was experienced due to eccentricity of the tread which developed because of unequal heating of the wheel. When hot it was out of round by as much as 0.01 of an inch, although it resumed its original form when cooled. This eccentricity was troublesome in the operation of the machine; but, what is more important, it caused an unequal distribution of heat in the wheel, because the shoe did more work on the high than on the low section of the tread.

For this reason the wheel, before being tested at higher pressures, was ground with greater care, the tolerable variation in diameter

being this time 0.0005 of an inch. The preliminary grinding of all other wheels was subsequently carried out with this same degree of accuracy. While the previous difficulty was thus avoided, the use of higher shoe pressures introduced a new one; for, after a few applications at 2000 pounds, shoe material was deposited here and there on the wheel tread and glazed spots developed in these places. Such spots had not appeared at all during tests at 1000 pounds pressure; and only toward the end of the series at 1500 pounds. They caused unequal heat distribution in the wheel (probably because of a lower coefficient of friction at these glazed areas), and again deformed the roundness of the tread. During subsequent tests on wheel No. 1—those at 3000 and 4000 pounds pressure—these glazed spots were removed after each application by polishing the tread with a sand-filled cleaning shoe, and then rubbing it lightly with an emery block. The emery block alone was found to suffice, and after each test with all the other wheels the glazed spots were removed by holding the block against the revolving tread.

In each of the 270 individual tests the testing machine was brought up to the desired speed, the brake was applied, and the wheel was kept running at uniform speed by manipulating the engine throttle. After running the desired time the machine was stopped. In tests for which subsequent temperature observations were not needed, the wheel was then cooled by revolving it slowly in an air blast. In those tests in which temperature readings were to be taken the wheel remained at rest, and the air blast was not used.

As previously stated, the tangential pull of the brake shoe is transmitted to a dynamometer which makes a graphical record of the pull. The integrator with which the machine is equipped makes a record of the area under this pull curve, which is proportional to the work performed by the shoe upon the wheel. The dynamometer chart also bears a time record which distinguishes one-second intervals. The records of pull, work, and time were taken during one minute at the beginning of the application, for the first minute of each subsequent ten-minute interval, and during the last two minutes of the test. In addition, the number of revolutions of the wheel and of the integrator counter were recorded at five-minute intervals during the run, as well as at its beginning and end. These data permit the calculation of tangential pull, coefficient of friction of the shoe, and the work performed by it.

9. *Procedure for Measurement of Temperature and Strains.*—Attention is again directed to the fact that temperature and strain observations were made on wheel No. 1 only. During 11 of the 150 tests run with this wheel, temperature observations were made, but without any measurements of strains. This was for the purpose of studying the variable distribution of heat in the wheel, which, in the earlier tests, caused the eccentricity to which reference has been made in Section 8. During 38 tests run with this wheel strains were measured, and also the corresponding temperatures, for the ultimate purpose of calculating the stresses developed.

In the eleven temperature distribution tests the temperatures were read while the wheel was running. In the temperature-strain tests the procedure was as follows: Temperature readings and gage-line measurements were taken immediately before the test; and the former were repeated at ten-minute intervals during its progress. When the test period was ended the brake shoe was released, and the wheel and the other revolving parts of the machine were allowed to drift to a stop. For the tests at 25 miles per hour this drifting period was about two minutes; for those at 15 miles, about one minute. As soon as the wheel came to rest the gage-lines were measured and temperature readings were taken; and these measurements and readings were repeated every ten minutes throughout the cooling period, which ended when temperatures throughout the wheel had become approximately alike. This cooling, as has been stated, went on in the still air of the laboratory, without the use of the air blast.

It was originally the intention, when planning to take these temperature–strain data, to record each time the readings for all 19 thermocouples and the measurements from the 40 corresponding gage-lines. This, however, proved to be impracticable; for the time required for all these strain measurements was so great that they could not be properly correlated with the temperature data. For this reason the temperature–strain observations taken for any one test are limited to measurements taken on both wheel faces in either one or the other of the two radial gage-line planes, or to those derived from the 8 gage-lines and 8 couples located in the rim of the wheel.

IV. Results of Tests

For the study of the endurance of the wheels under repeated brake applications, the treads were periodically examined and photographed; the condition of the checks and cracks was observed, and their number recorded. While the attempt is here made to express these observations verbally and to summarize them in tabular form, chief reliance is placed upon the accompanying reproductions of photographs and drawings to convey this information. The results of the temperature–strain determinations are likewise presented graphically, and the maximum strains found are cited in Table 9.

10. *Results of Tread Endurance Determinations.*—Wheel No. 1 was subjected successively to pressures of 1000, 1500, 2000, 3000, and 4000 pounds. The ninety brake shoe applications at the lowest three pressures (30 each) did not greatly damage the tread of this wheel. A few small checks developed during the tests at 1000 and 1500 pounds; and a few more, together with a few small cracks, were produced during the 2000-pound series.

After the 3000-pound series a large number of heat checks and cracks were found on the tread of this wheel. Thirty-two of the cracks were longer than 2¾ inches, which is the condemning limit specified in the Wheel and Axle Manual of the Association of American Railroads. When again examined, after the tests at 4000 pounds shoe pressure, 92 cracks over 2¾ inches in length were found. None of them extended into the throat or the flange, although 16 ran to the outside edge of the wheel rim.

Figure 4 presents reproductions of 5 scaled drawings of the entire tread of wheel No. 1, which show the condition of the tread after the completion of each of the five test series; that is, after being successively subjected to each of the five pressures cited. The progressive deterioration of the tread of this wheel is also shown in the series of photographs which are reproduced in Figs. 6 to 8 inclusive. From this series, however, illustrations of the tread of this wheel after the tests at 1000 pounds shoe pressure (Series 3500) are omitted, since this pressure produced no visible damage. The photographs, although they show only a small portion of the tread, are fairly characteristic of its condition throughout the circumference. The photographs reproduced in Figs. 6 to 8 were taken at thermocouple No. 14. The black lines shown in these (and subsequent) tread illustrations are reference lines drawn from a thermocouple or quadrant, in order to facilitate comparisons between successive photographs of each series.

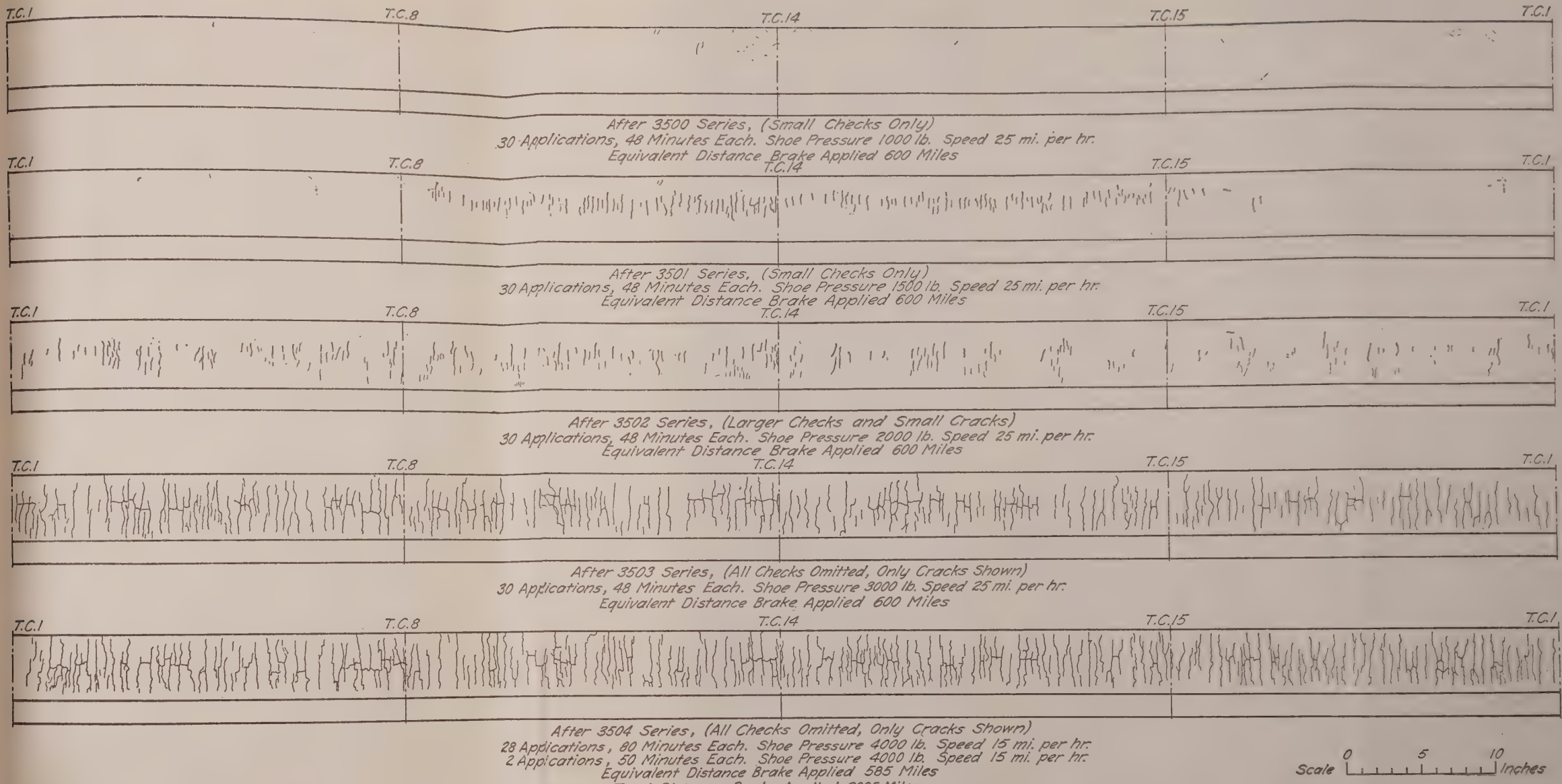
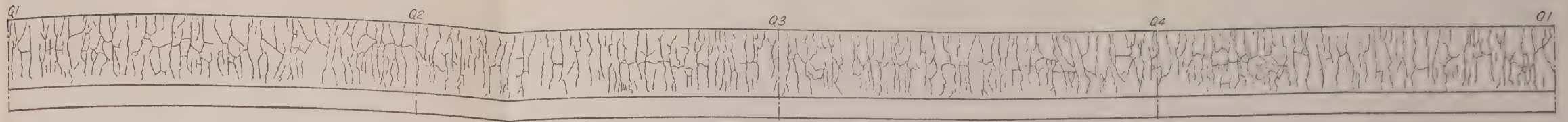
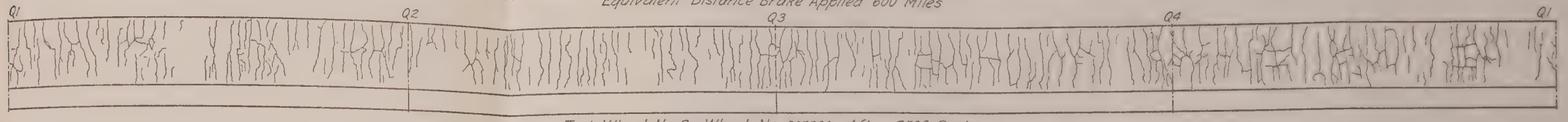

T.C.1
T.C.8
T.C.14
T.C.15
T.C.1
After 3500 Series, (Small Checks Only)
30 Applications, 48 Minutes Each. Shoe Pressure 1000 lb. Speed 25 mi. per hr.
Equivalent Distance Brake Applied 600 Miles
After 3501 Series, (Small Checks Only)
30 Applications, 48 Minutes Each. Shoe Pressure 1500 lb. Speed 25 mi. per hr.
Equivalent Distance Brake Applied 600 Miles
After 3502 Series, (Larger Checks and Small Cracks)
30 Applications, 48 Minutes Each. Shoe Pressure 2000 lb. Speed 25 mi. per hr.
Equivalent Distance Brake Applied 600 Miles
After 3503 Series, (All Checks Omitted, Only Cracks Shown)
30 Applications, 48 Minutes Each. Shoe Pressure 3000 lb. Speed 25 mi. per hr.
Equivalent Distance Brake Applied 600 Miles
After 3504 Series, (All Checks Omitted, Only Cracks Shown)
28 Applications, 80 Minutes Each. Shoe Pressure 4000 lb. Speed 15 mi. per hr.
2 Applications, 50 Minutes Each. Shoe Pressure 4000 lb. Speed 15 mi. per hr.
Equivalent Distance Brake Applied 585 Miles
Total Distance Brake Applied 2985 Miles
Scale 0 5 10 Inches

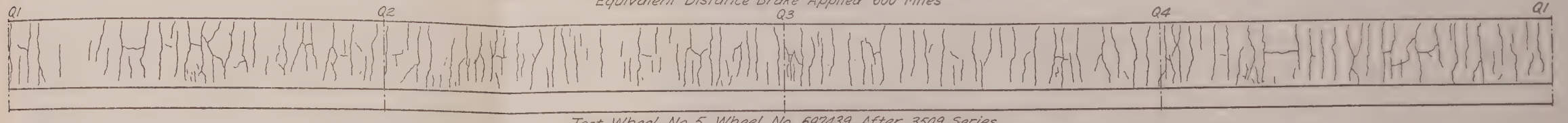
FIG. 4. CONDITION OF TREAD OF WHEEL NO. 1 AFTER EACH SERIES OF TESTS



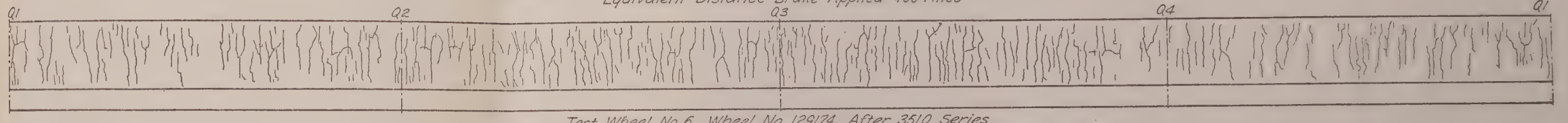
Test Wheel No. 2, Wheel No. A-23681. After 3505 Series
30 Applications, 48 Minutes Each. Shoe Pressure 3000 lb. Speed 25 mi. per hr.
Equivalent Distance Brake Applied 600 Miles



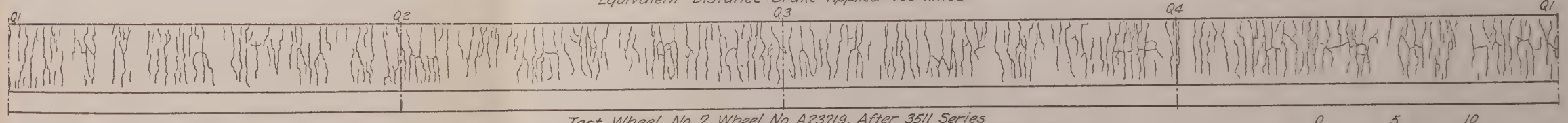
Test Wheel No. 3, Wheel No. 697388. After 3506 Series
30 Applications, 48 Minutes Each. Shoe Pressure 3000 lb. Speed 25 mi. per hr.
Equivalent Distance Brake Applied 600 Miles



Test Wheel No. 5, Wheel No. 697439. After 3509 Series
20 Applications, 48 Minutes Each. Shoe Pressure 3000 lb. Speed 25 mi. per hr.
Equivalent Distance Brake Applied 400 Miles



Test Wheel No. 6, Wheel No. 129174. After 3510 Series
20 Applications, 48 Minutes Each. Shoe Pressure 3000 lb. Speed 25 mi. per hr.
Equivalent Distance Brake Applied 400 Miles



Test Wheel No. 7, Wheel No. A23719. After 3511 Series
20 Applications, 48 Minutes Each. Shoe Pressure 3000 lb. Speed 25 mi. per hr.
Equivalent Distance Brake Applied 400 Miles

Note: All Checks Omitted,
Only Cracks Shown.

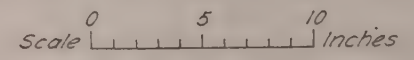


Fig. 5. Condition of Treads of Wheels Nos. 2, 3, 5, 6, and 7 After Tests

TABLE 6
RECORD OF CRACKS LONGER THAN 2¾ INCHES ON THE TREADS OF WHEELS NOS. 2, 3, 5, 6, AND 7

Wheel 2		Wheel 3		Wheel 5		Wheel 6		Wheel 7	
After Application No.	Number of Cracks	After Application No.	Number of Cracks	After Application No.	Number of Cracks	After Application No.	Number of Cracks	After Application No.	Number of Cracks
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
..	..	..	..	..	..	..	..	9	23
10	None	10	None	10	None	10	None	..	..
..	..	..	..	..	..	..	..	11	41
16	43	16	38	..	..	15	48	15	95
20	97	20	73	20	98	20	71	20	116
25	106	25	106	..	..	..	..	..	..
30	120	30	111	..	..	..	..	..	..

It will be recalled that the other wheels, Nos. 2, 3, 5, 6, and 7, were tested at 3000 pounds shoe pressure only; Nos. 2 and 3 being given 30 applications each—equivalent to 600 miles of braking, while Nos. 5, 6 and 7 were given 20 applications each—equivalent to 400 miles. Table 6 shows for each of these wheels the number of cracks longer than 2¾ inches which developed in its tread at various stages of its testing. Figure 5 reproduces scaled drawings of the treads of each of these wheels after the work with it had been completed. The progress of their checking and cracking is shown by the reproductions of photographs which constitute Figs. 9 to 13 inclusive. These show for each wheel the condition of a section of its tread after each five shoe applications; that is, after the equivalent of each 100 miles of brake application. The relation of these figures to the wheels is as follows:

Figure 9 relates to wheel No. 2.
Figure 10 relates to wheel No. 3.
Figure 11 relates to wheel No. 5.
Figure 12 relates to wheel No. 6.
Figure 13 relates to wheel No. 7.

Of the photographs of the tread of wheel No. 2, those for Figs. 9b-9f were taken of the same section of the tread; whereas that for Fig. 9a was taken of a section about 13 inches away therefrom. For each of the other wheels the related photographs are of the same section of the wheel tread.

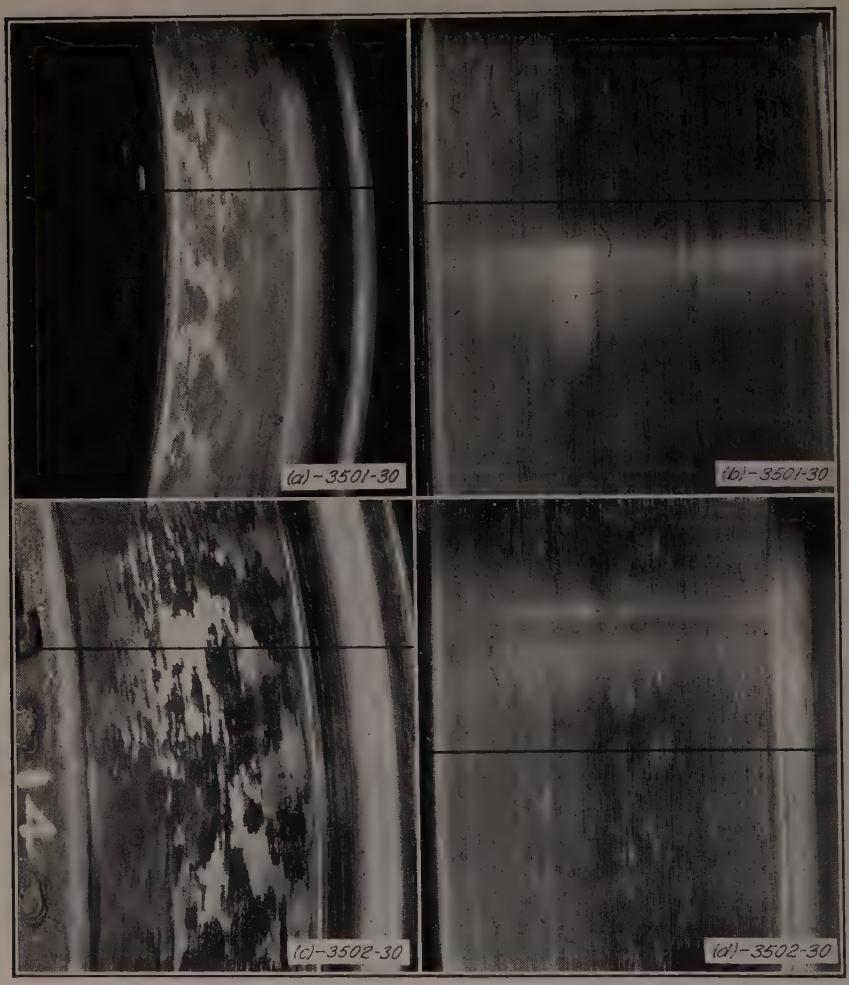


FIG. 6. CONDITION OF TREAD OF WHEEL NO. 1 AFTER TESTS, SERIES 3501-30 AND 3502-30

During each application the brake shoe was continuously applied for a distance of 20 miles, with the wheel running constantly at 25 m.p.h.

(a) After 60 applications—30 applications with 1000 lb., and 30 with 1500 lb. shoe pressure, making a total distance of 1200 miles with the brake applied.

(c) After 90 applications—30 applications with 1000 lb., 30 with 1500 lb., and 30 with 2000 lb. shoe pressure, making a total distance of 1800 miles with the brake applied.

(b) and (d) The same as (a) and (c) but after grinding the tread.

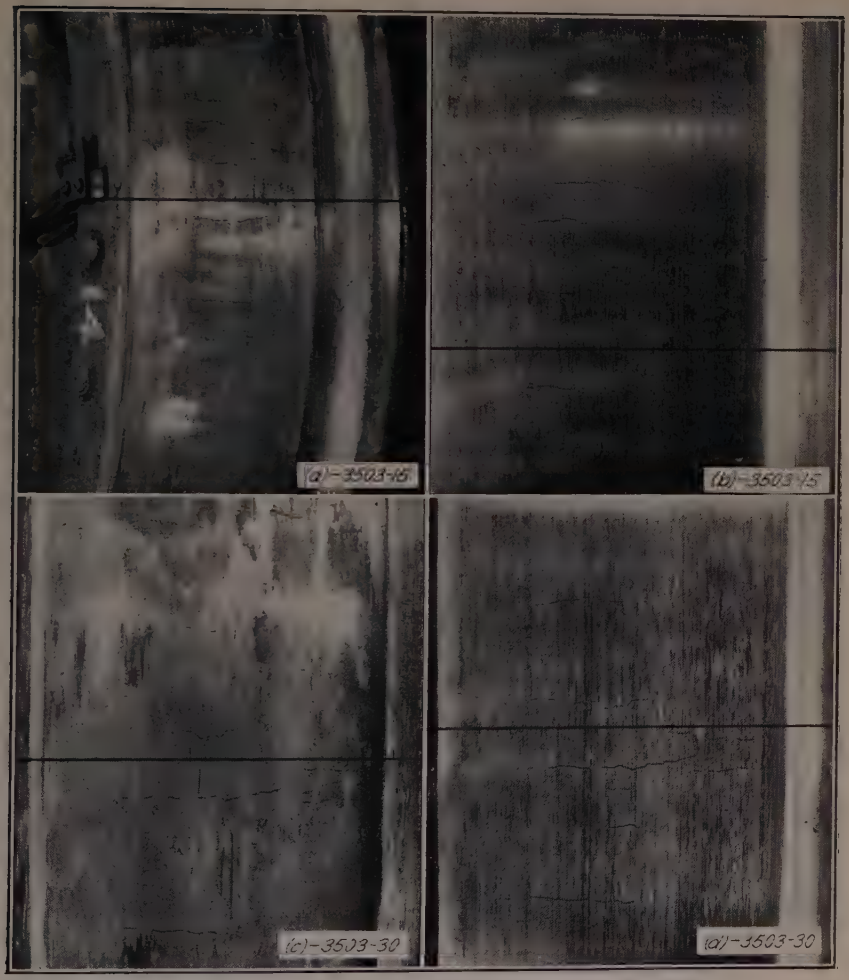


FIG. 7. CONDITION OF TREAD OF WHEEL NO. 1 AFTER TESTS, SERIES 3503-15 AND 3503-30

During each application the brake shoe was continuously applied for a distance of 20 miles, with the wheel running constantly at 25 m.p.h.

(a) After 105 applications—30 applications with 1000 lb., 30 with 1500 lb., 30 with 2000 lb., and 15 with 3000 lb. shoe pressure, making a total distance of 2100 miles with the brake applied.

(c) After 120 applications—30 applications with 1000 lb., 30 with 1500 lb., 30 with 2000 lb., and 30 with 3000 lb. shoe pressure, making a total distance of 2400 miles with the brake applied.

(b) and (d) The same as (a) and (c) but after polishing the tread.

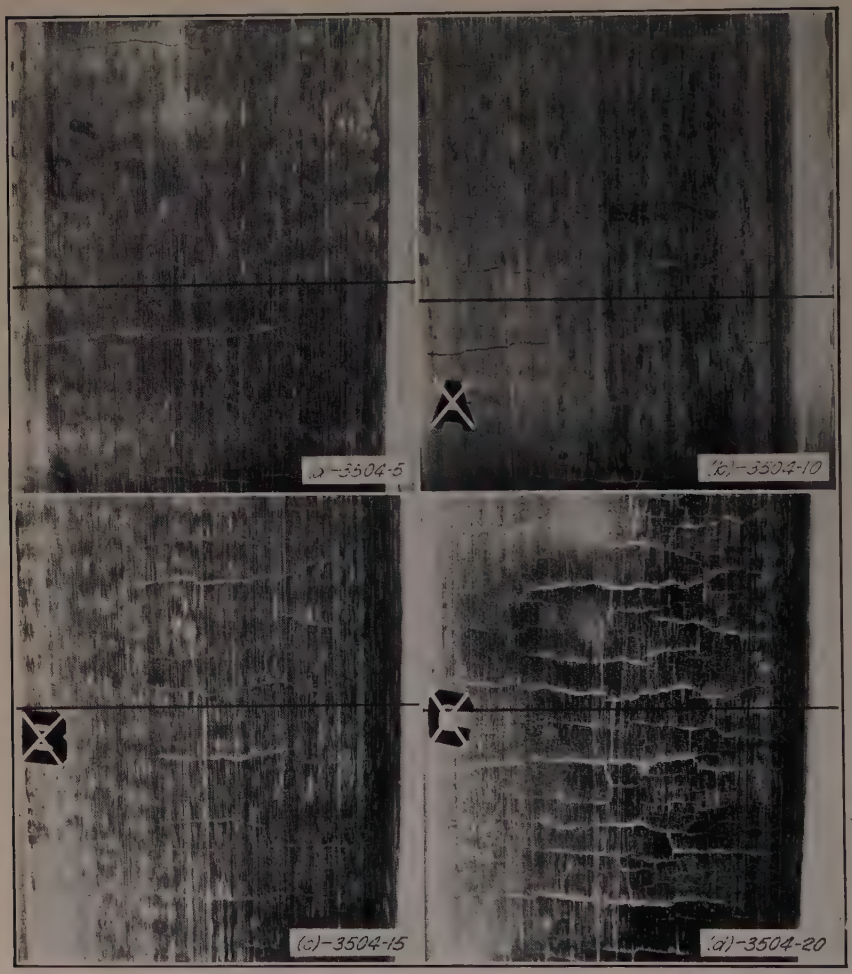


FIG. 8. CONDITION OF TREAD OF WHEEL NO. 1 AFTER APPLICATIONS NOS. 5, 10, 15, AND 20 OF THE 3504 TEST SERIES, AFTER POLISHING TREAD

(a) After 125 applications—30 applications with 1000 lb., 30 with 1500 lb., 30 with 2000 lb., and 30 with 3000 lb. shoe pressure, with the wheel running continuously at 25 m.p.h., and 5 applications with 4000 lb. at 15 m.p.h. During each application the brake shoe was applied for a distance of 20 miles, making a total distance of 2500 miles with the brake applied.

(b) Same as (a) but with 4 additional applications of 20 miles each and one of 12.5 miles, all at 15 m.p.h. with 4000 lb. shoe pressure, making a total distance of 2592.5 miles with the brake applied.

(c) Same as (b) but with 5 additional applications of 20 miles each at 15 m.p.h. with 4000 lb. shoe pressure, making a total distance of 2692.5 miles with the brake applied.

(d) Same as (c) but with 4 additional applications of 20 miles each and one of 12.5 miles, all at 15 m.p.h. with 4000 lb. shoe pressure, making a total distance of 2785 miles with the brake applied.

FIG. 8 (CONCLUDED). CONDITION OF TREAD OF WHEEL NO. 1 AFTER APPLICATIONS NOS. 25 AND 30 OF THE 3504 TEST SERIES, AFTER POLISHING TREAD

(e) Same as Fig. 8 (d) but with 5 additional applications of 20 miles each at 15 m.p.h. with 4000 lb. shoe pressure, making a total distance of 2885 miles with the brake applied.

(f) Same as (e) but with 5 additional applications of 20 miles each at 15 m.p.h. with 4000 lb. shoe pressure, making a total distance of 2985 miles with the brake applied.

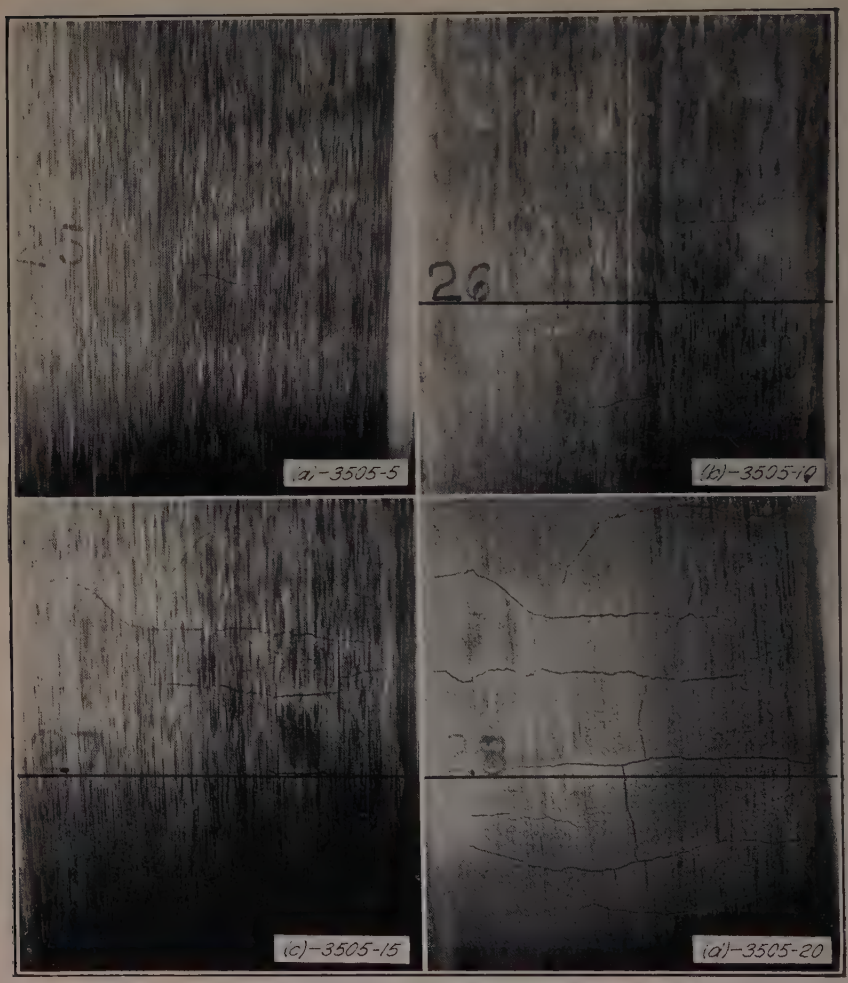


FIG. 9. CONDITION OF TREAD OF WHEEL NO. 2 AFTER APPLICATIONS NOS. 5, 10, 15, AND 20 OF THE 3505 TEST SERIES, AFTER POLISHING TREAD

During each application the brake shoe was continuously applied with 3000 lb. pressure for a distance of 20 miles, with the wheel running constantly at 25 m.p.h.

(a) After 5 applications, making a total distance of 100 miles.
(b) After 10 applications, making a total distance of 200 miles.
(c) After 15 applications, making a total distance of 300 miles.
(d) After 20 applications, making a total distance of 400 miles.

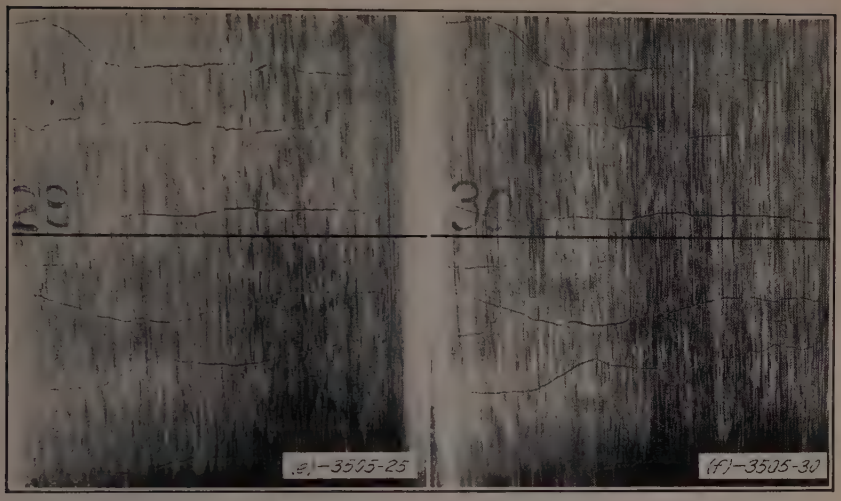


FIG. 9 (CONCLUDED). CONDITION OF TREAD OF WHEEL NO. 2 AFTER APPLICATIONS NOS. 25 AND 30 OF THE 3505 TEST SERIES, AFTER POLISHING TREAD

(e) After 25 applications, making a total distance of 500 miles.
(f) After 30 applications, making a total distance of 600 miles.

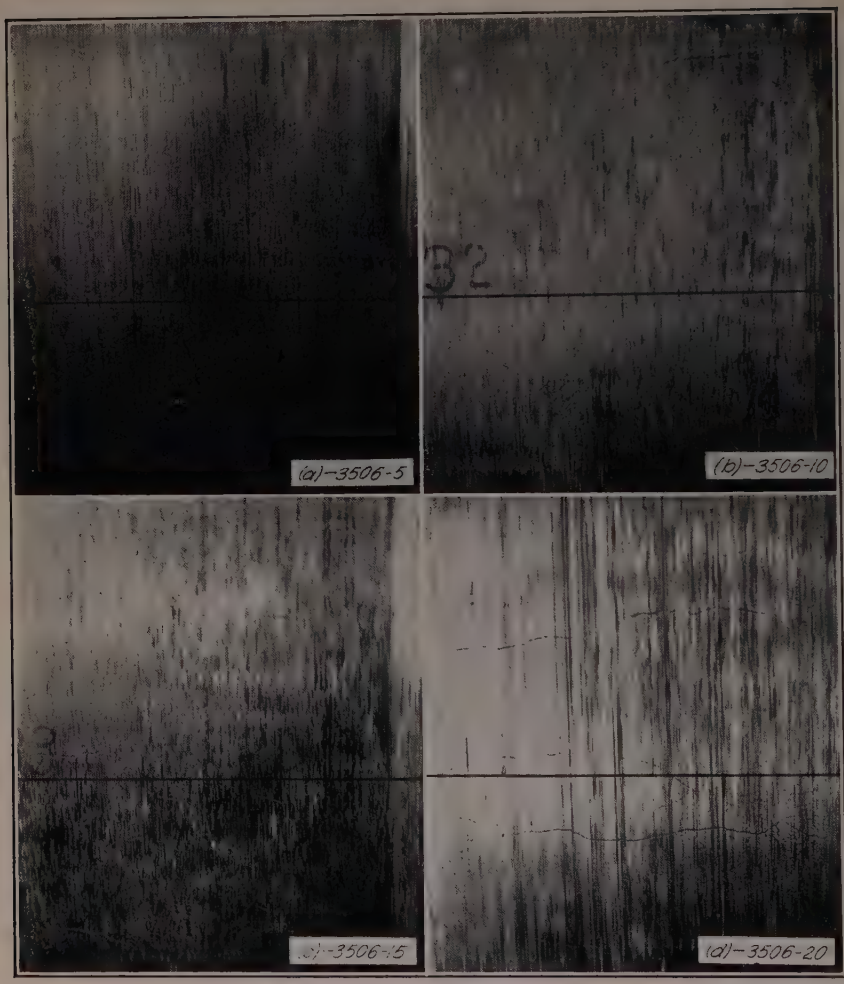


FIG. 10. CONDITION OF TREAD OF WHEEL NO. 3 AFTER APPLICATIONS NOS. 5, 10, 15, AND 20 OF THE 3506 TEST SERIES, AFTER POLISHING TREAD

During each application the brake shoe was continuously applied with 3000 lb. pressure for a distance of 20 miles, with the wheel running constantly at 25 m.p.h.

(a) After 5 applications, making a total distance of 100 miles.
(b) After 10 applications, making a total distance of 200 miles.
(c) After 15 applications, making a total distance of 300 miles.
(d) After 20 applications, making a total distance of 400 miles.

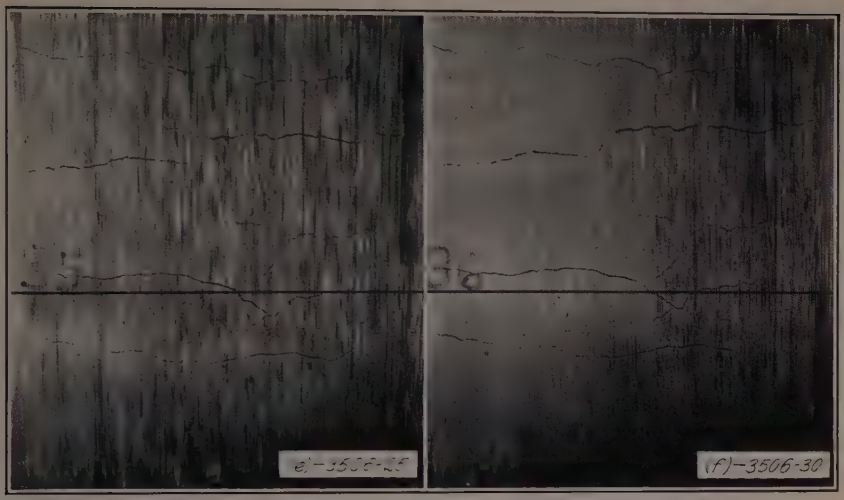


FIG. 10 (CONCLUDED). CONDITION OF TREAD OF WHEEL NO. 3 AFTER APPLICATIONS NOS. 25 AND 30 OF THE 3506 TEST SERIES, AFTER POLISHING TREAD

(e) After 25 applications, making a total distance of 500 miles.
(f) After 30 applications, making a total distance of 600 miles.

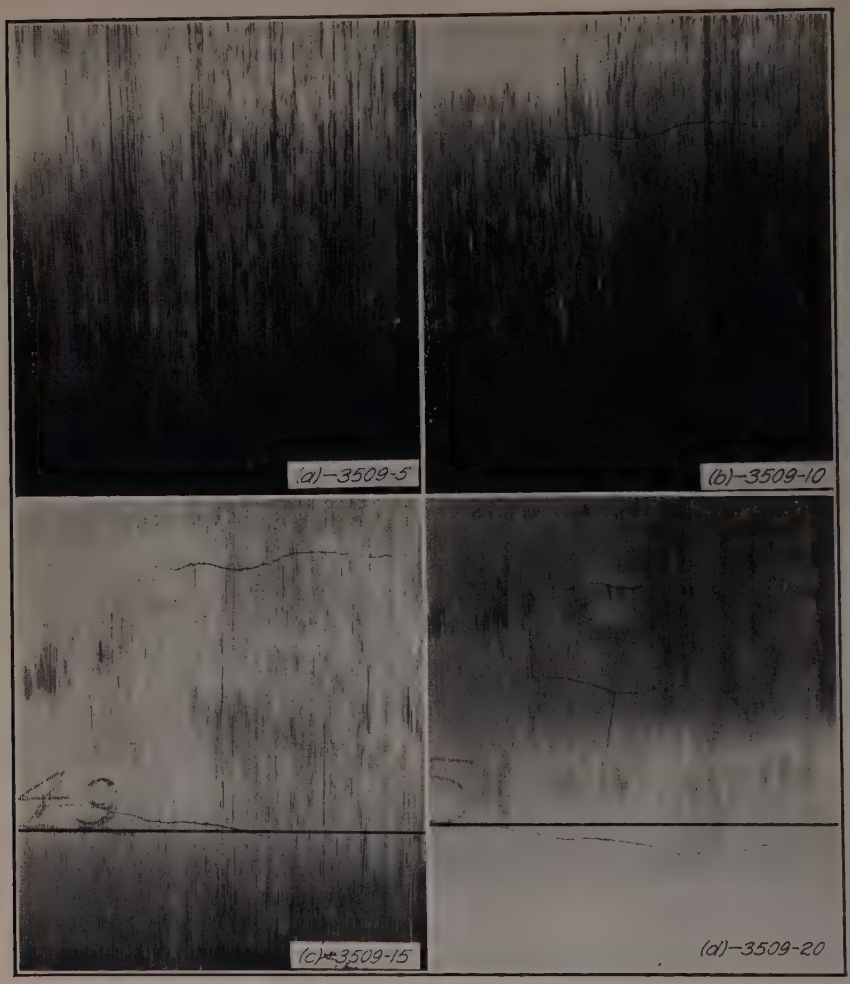


FIG. 11. CONDITION OF TREAD OF WHEEL NO. 5 AFTER APPLICATIONS NOS. 5, 10, 15, AND 20 OF THE 3509 TEST SERIES, AFTER POLISHING TREAD

During each application the brake shoe was continuously applied with 3000 lb. pressure for a distance of 20 miles, with the wheel running constantly at 25 m.p.h.

(a) After 5 applications, making a total distance of 100 miles.
(b) After 10 applications, making a total distance of 200 miles.
(c) After 15 applications, making a total distance of 300 miles.
(d) After 20 applications, making a total distance of 400 miles.

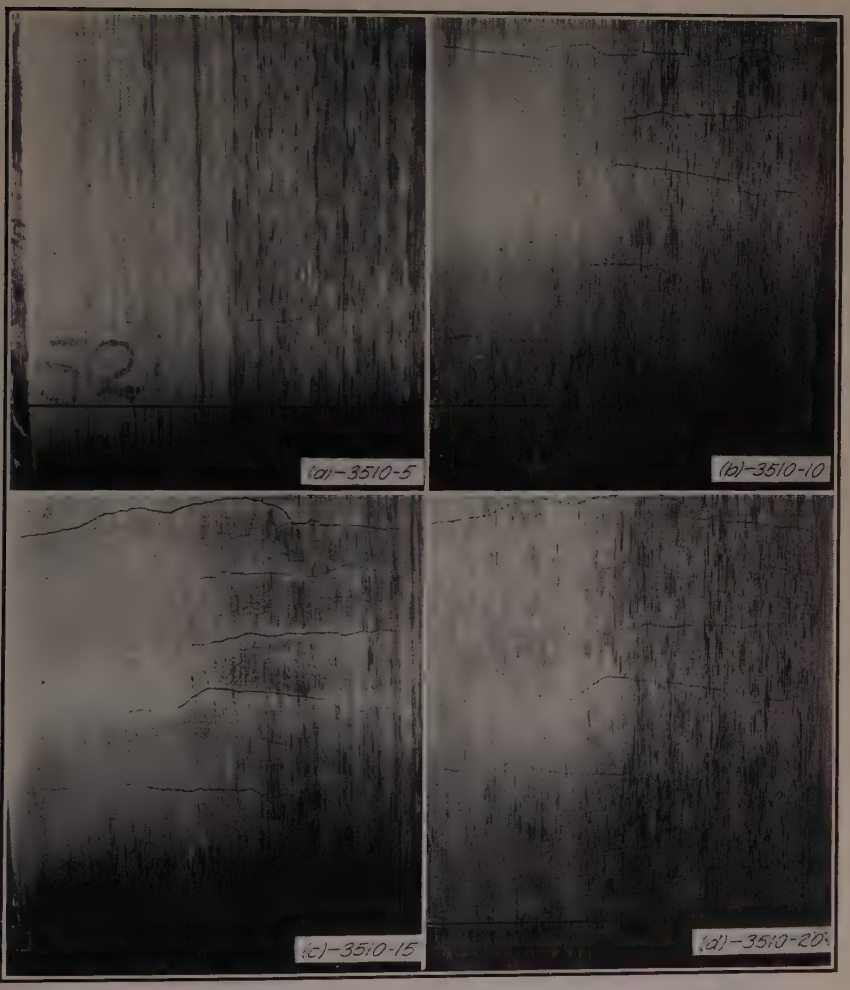


FIG. 12. CONDITION OF TREAD OF WHEEL NO. 6 AFTER APPLICATIONS NOS. 5, 10, 15, AND 20 OF THE 3510 TEST SERIES, AFTER POLISHING TREAD

During each application the brake shoe was continuously applied with 3000 lb. pressure for a distance of 20 miles, with the wheel running constantly at 25 m.p.h.

(a) After 5 applications, making a total distance of 100 miles.
(b) After 10 applications, making a total distance of 200 miles.
(c) After 15 applications, making a total distance of 300 miles.
(d) After 20 applications, making a total distance of 400 miles.

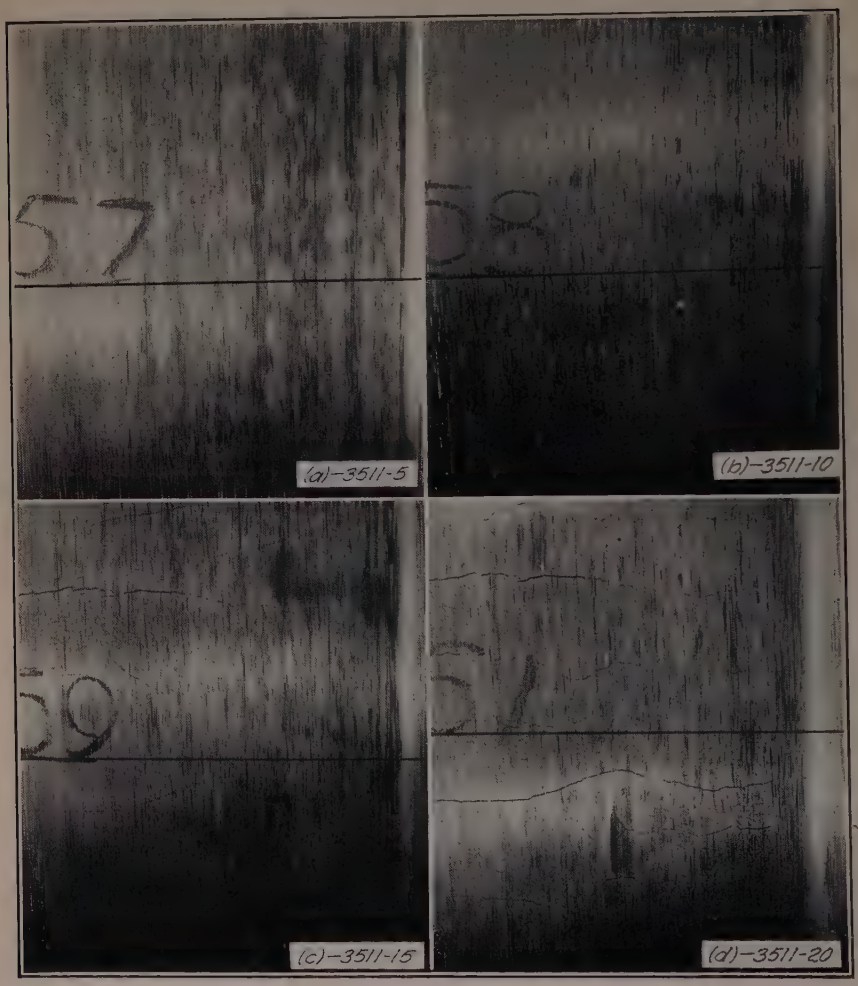


FIG. 13. CONDITION OF TREAD OF WHEEL NO. 7 AFTER APPLICATIONS NOS. 5, 10, 15, AND 20 OF THE 3511 TEST SERIES, AFTER POLISHING TREAD

During each application the brake shoe was continuously applied with 3000 lb. pressure for a distance of 20 miles, with the wheel running constantly at 25 m.p.h.

(a) After 5 applications, making a total distance of 100 miles.
(b) After 10 applications, making a total distance of 200 miles.
(c) After 15 applications, making a total distance of 300 miles.
(d) After 20 applications, making a total distance of 400 miles.

Some of the principal general results of the tests of all six wheels are presented in Table 7. This summary includes, for each of the test series, average values of speed, coefficient of friction, total work performed upon the wheels by the brake shoes, shoe wear per application, and shoe wear per million foot-pounds of work performed. In view of the severity of some of the test conditions, it is significant that throughout the investigation no comby spots or shell-outs developed on any of the wheels.

Table 8 is here presented in order to facilitate comparison of the conditions which prevailed in these tests with conditions which might prevail in actual service. Columns 5 and 6 of this table are headed "Equivalent Grade Per Cent." This equivalent grade is the grade down which a car, of the gross weight listed in the table, would descend at the uniform speed given in column 3 when the brake shoe pressure on each of the eight wheels of the car is that given in column 2.

In calculating the equivalent grade for column 5 the car was assumed to be a 40-ton capacity refrigerator car of 56 000 pounds light weight, with a load of 40 000 pounds. A retarding effect of 5.2 pounds per ton at 25 miles per hour and of 4.4 pounds per ton at 15 miles per hour,* due to train resistance, was assumed in calculating the equivalent grade. In calculating column 6, the same car was assumed to be loaded to its capacity of 80 000 pounds; the retarding effect due to train resistance in this case being 4.1 pounds per ton at 25 miles per hour, and 3.5 pounds per ton at 15 miles per hour. The equivalent grades in all cases were assumed to be continuous tangent grades 20 miles long.

The equivalent gross weight of car on grades of 2, 2.5 and 3 per cent is shown in columns 7, 8 and 9. From column 7 it may be seen that the brake action during the 3500 series corresponds to the brake action on the wheels of a car of a gross weight of 95 000 pounds in going down 30 separate 2-per-cent grades 20 miles long.

11. *Measurements of Temperatures and Strains.*—The method of measuring temperatures and strains has been explained in Chapter III. Such measurements were taken during 38 of the tests made on wheel No. 1. They included all combinations of shoe pressure and speed used on that wheel. Of these 38 tests, thirteen, which in test conditions and results are typical of the whole group, are here presented and discussed. These 13 tests are listed in Table 9, which shows also, in

*From Bulletin 43, University of Illinois Engineering Experiment Station, "Freight Train Resistance, Its Relation to Car Weight."

TABLE 7
GENERAL RESULTS

Series No.	Test Wheel No.	Brake Shoe Pressure lb.	Average Speed m.p.h.	Average Coefficient of Friction per cent	Total Work millions of foot-pounds	Average Shoe Wear per Application lb.	Shoe Wear in Lb. per 100 Millions Ft. Lb. of Work
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
3500	1	1000	24.44	20.64	638.94	0.052	0.244
3501	1	1500	24.99	20.97	996.14	0.122	0.368
3502	1	2000	25.00	19.84	1257.27	0.222	0.530
3503	1	3000	25.00	15.69	1490.75	0.460	0.926
3504	1	4000	14.97	17.87	2201.22	0.695	1.091
		Total work, Wheel No. 1..... 6584.32					
3505	2	3000	24.99	17.15	1629.15	0.492	0.906
3506	3	3000	25.02	17.64	1677.58	0.548	0.980
3509	5	3000	24.99	16.02	1076.98	0.500	0.930
3510	6	3000	25.00	17.44	1105.02	0.463	0.838
3511	7	3000	25.00	17.96	1137.36	0.509	0.896

TABLE 8
RAILWAY OPERATING CONDITIONS SIMILAR TO CONDITIONS UNDER WHICH TESTS WERE MADE

Series No.	Brake Shoe Pressure lb.	Average Speed m.p.h.	Average Tangential Pull lb.	Equivalent Grade in Per Cent for Cars of Gross Weight of		Equivalent Gross Weight of Car in Pounds on Grade of		
				48 Tons	68 Tons	2 Per Cent	2.5 Per Cent	3 Per Cent
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
3500	1000	24.44	206.4	1.988	1.464	95 000	76 600	62 800
3501	1500	24.99	314.6	2.890	2.042	140 000	111 000	92 000
3502	2000	25.00	396.8	3.575	2.584	175 000	138 000	114 000
3503	3000	25.00	470.7	4.191	3.019	204 000	163 000	134 800
3504	4000	14.97	714.8	6.177	4.380	299 000	239 000	199 400
3505	3000	24.99	514.4	4.555	3.276	221 800	176 800	146 800
3506	3000	25.02	529.3	4.679	3.364	228 000	182 000	151 200
3509	3000	24.99	480.5	4.273	3.076	208 000	166 000	137 000
3510	3000	25.00	523.3	4.629	3.328	225 600	180 000	149 600
3511	3000	25.00	538.4	4.755	3.417	231 600	184 800	153 800

TABLE 9
SUMMARY OF RESULTS OF STRAIN TESTS

	Series No.	Application No.	Brake Shoe Pressure lb.	Average Speed m.p.h.	Distance With Brake Applied miles	Average Coefficient of Friction per cent	Total Work millions of ft.-lb.	Shoe Wear in Pounds per 100 Million Ft.-Lb. of Work	Temperature Diff. Between Couples on Stopping deg. F.		Maximum Unit Tensile Strain on Stopping	
									Couples 2 and 6	Couples 9 and 13	inches per inch	Gage Line Location
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Chilled Wheel No. 1	3500	17	1000	24.35	19.48	20.70	21.291	0.2818	151	...	0.00100	06R
	3500	18	1000	24.32	19.46	20.90	21.473	0.2329	...	197	0.00111	013R
	3501	22	1500	25.00	20.00	21.73	34.422	0.3777	209	...	0.00202	06R
	3501	25	1500	24.96	19.97	22.07	34.899	0.3438	...	331	0.00179	013R
	3502	27	2000	24.98	19.99	20.55	43.373	0.5303	365	...	0.00292	06R
	3502	28	2000	25.01	20.01	20.35	42.996	0.4884	...	396	0.00296	013R
	3503	17	3000	25.01	20.01	14.63	46.373	1.0998	458	...	0.00275	06R
	3503	5	3000	25.00	20.00	16.43	52.056	0.8645	...	500	0.00320	013R
	3503	25	3000	25.00	20.00	16.17	51.228	0.8979	...	...	0.00112	014T
	3504	1	4000	14.97	19.96	18.20	76.709	0.8343	410	...	0.00346	06R
	3504	5	4000	14.96	19.95	17.68	74.454	0.8730	...	488	0.00310	013R
	3504	6	4000	14.96	12.47	17.73	46.671	0.7714	440	...	0.00430	06R
	3504	16	4000	14.97	12.48	17.18	45.265	0.7953	...	491	0.00301	013R

columns 11 and 12, the magnitude and location of the maximum tensile strains produced in these tests, and in columns 5 to 8 the corresponding average values of equivalent mileage, coefficient of friction, work performed by the shoe, and shoe wear.

For each of these 13 tests the complete record of temperatures measured and the corresponding strains developed are given in Figs. 14 to 20 inclusive. For example, the temperature–strain data for tests Nos. 3500-17 and 3500-18 (the first pair of tests listed in Table 9) are presented in Fig. 14. The curves in the upper left-hand corner give the temperatures recorded during test No. 3500-17, from its beginning to the end of the cooling period. These temperatures were measured on one radius of wheel No. 1 (see Fig. 1). The curves in the upper right-hand corner give the temperature measurements made during test No. 3500-18, which was made under the same conditions of shoe pressure and speed as prevailed in test No. 3500-17; the temperatures, however, were measured along a radius at right angles to that employed in its companion test. The lower curves show, for each of these two tests, both the radial and the tangential strains developed during the cooling period after the brake was released. The strains were measured on both faces of the wheel. The strains for test No. 3500-17 appear on the left side—those for the outer face of the wheel, at the extreme left, those for the inner face, at the left center. The strains for test No. 3500-18 are similarly plotted on the right side of this figure. All the strains plotted in Fig. 14 are unit strains, expressed as inches per inch of wheel material. In this figure radial strains are shown by the curves drawn in full lines, tangential strains, by those drawn in broken lines.

In the upper portion of Fig. 14 are drawn curves of "Friction." The points defining these curves are average values of the coefficient of brake shoe friction during successive five-minute intervals of the test, derived from the tangential pull curve produced on the dynamometer record. In the upper center of this figure are curves showing the cumulative work done by the shoe upon the wheel. These are nearly straight lines; the variations therefrom being due to slight changes in the coefficient of shoe friction during the progress of the tests.

The foregoing explanations and comments for Fig. 14 apply to the first pair of tests listed in Table 9, namely, Nos. 3500-17 and 3500-18. If, from Table 9, test No. 3503-25 be omitted, these explanations and

comments apply equally, for each successive pair of tests in the table, to Figs. 14 to 19 inclusive. These relationships are as follows:

Figure 14 relates to tests 3500-17 and 3500-18.
Figure 15 relates to tests 3501-22 and 3501-25.
Figure 16 relates to tests 3502-27 and 3502-28.
Figure 17 relates to tests 3503-5 and 3503-17.
Figure 18 relates to tests 3504-1 and 3504-5.
Figure 19 relates to tests 3504-6 and 3504-16.

The remaining figure in this sequence, Fig. 20, applies to test No. 3503-25; and shows the temperatures and the tangential strains in the rim of wheel No. 1.

Recurring to Table 9, we find that the maximum radial tensile strains disclosed by these data occur always at either gage-line 0-6-R or gage-line 0-13-R, both of which were located on the outer face of the wheel, near the curved junction of the plate with the hub. In all the tests the maximum radial strain produced was a tensile strain of 0.0043 inches per inch which occurred in test No. 3504-6, run at 4000 pounds pressure and 15 miles per hour, with the shoe applied for 50 minutes. Figure 21 shows the general distribution and the general relative magnitude of the radial strains set up on both faces of the plate of the wheel. The maximum radial tensions occur on the outer face; while the maximum radial compressions occur on the inner face. Passing from the rim toward the hub, the radial stress on the inner face changes from tension to compression; whereas, on the outer face, the surface of the plate is in moderate compression, which, after diminishing to the neutral point, changes to greater and greater tension as the hub is approached. All the *tangential* strains produced during the investigation were relatively small, as compared with the radial strains. The maximum strain found upon stopping the wheel increases as the temperature difference between tread and hub increases. In the special tests 3504-6 and 3504-16, which were of 50 minutes duration, this temperature difference and the resulting strain were greater than those found in the regular tests of the 3504 series, which lasted for 80 minutes.

The ultimate usefulness of these strain measurements lies in the determination, for purposes of design, of the corresponding stresses in the wheel material. In the tests the measured elongation of any gage-line is in part due to the actual tension in the material and in

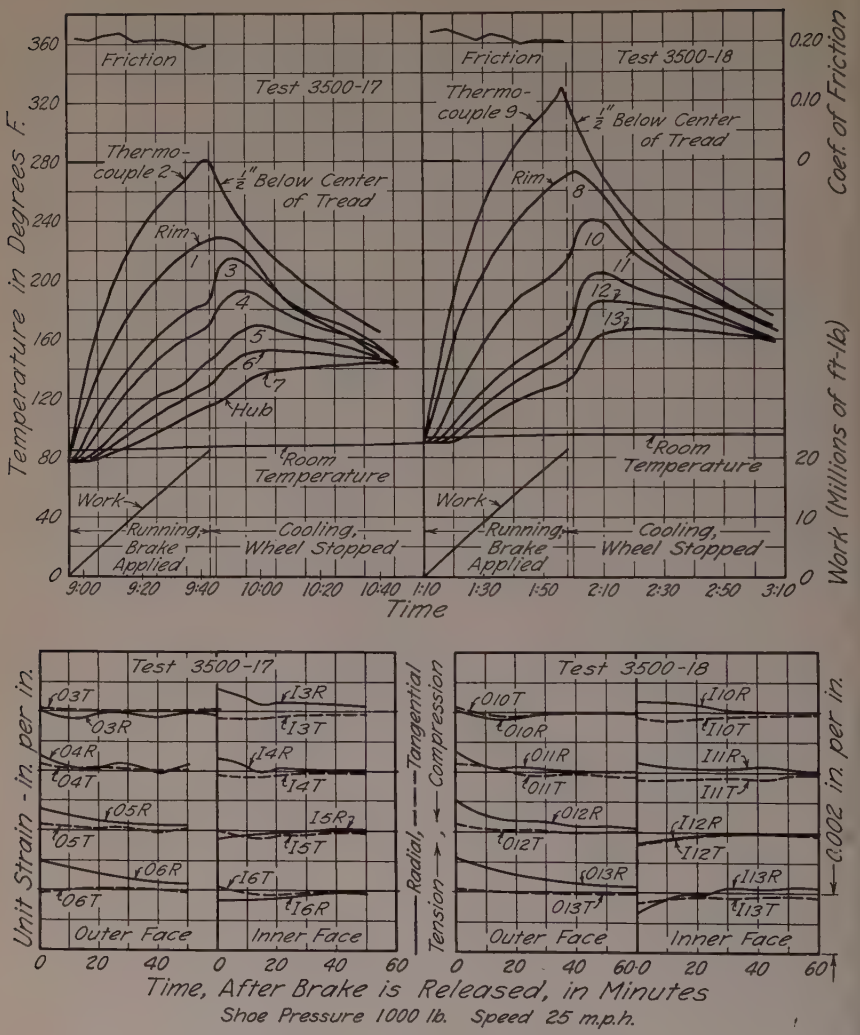


FIG. 14. RESULTS OF TESTS 3500-17 AND 3500-18

For a detailed explanation of these curves see pages 36, 37, and 45.

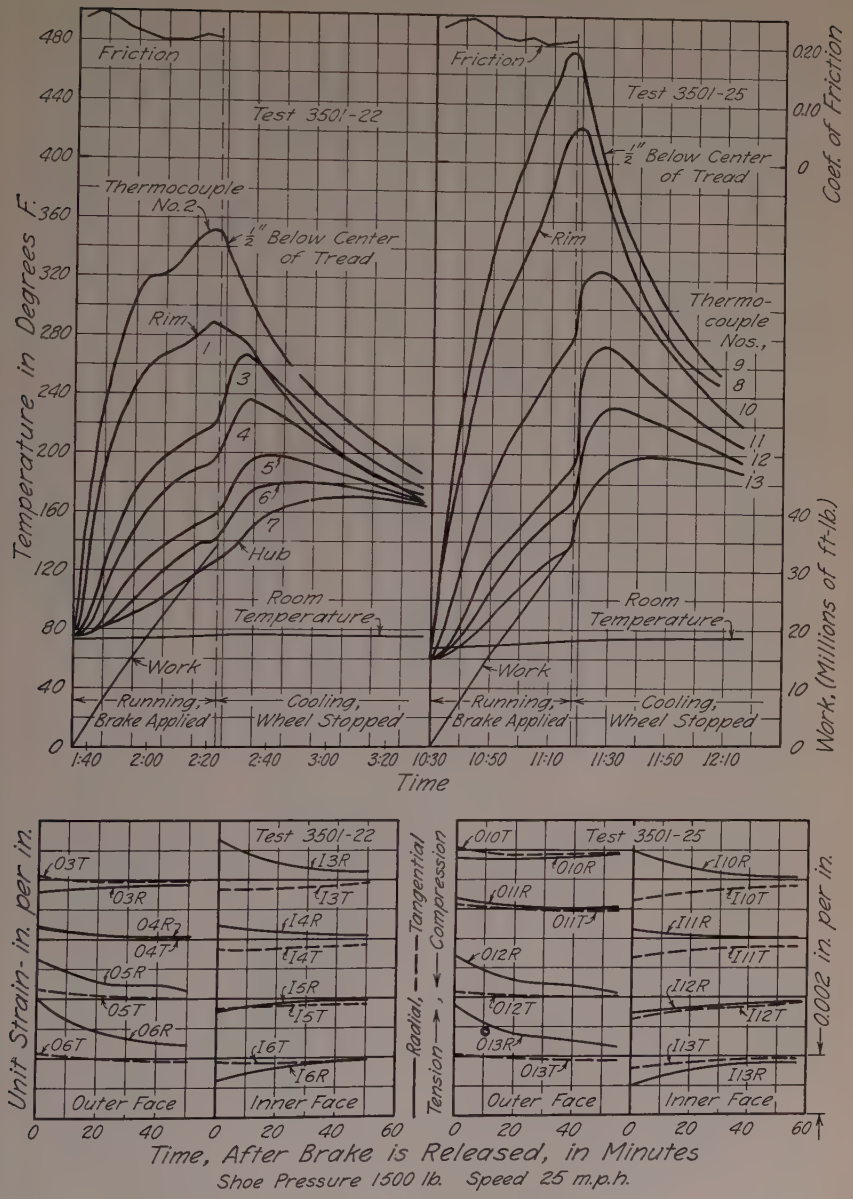


FIG. 15. RESULTS OF TESTS 3501-22 AND 3501-25

For a detailed explanation of these curves see pages 36, 37, and 45.

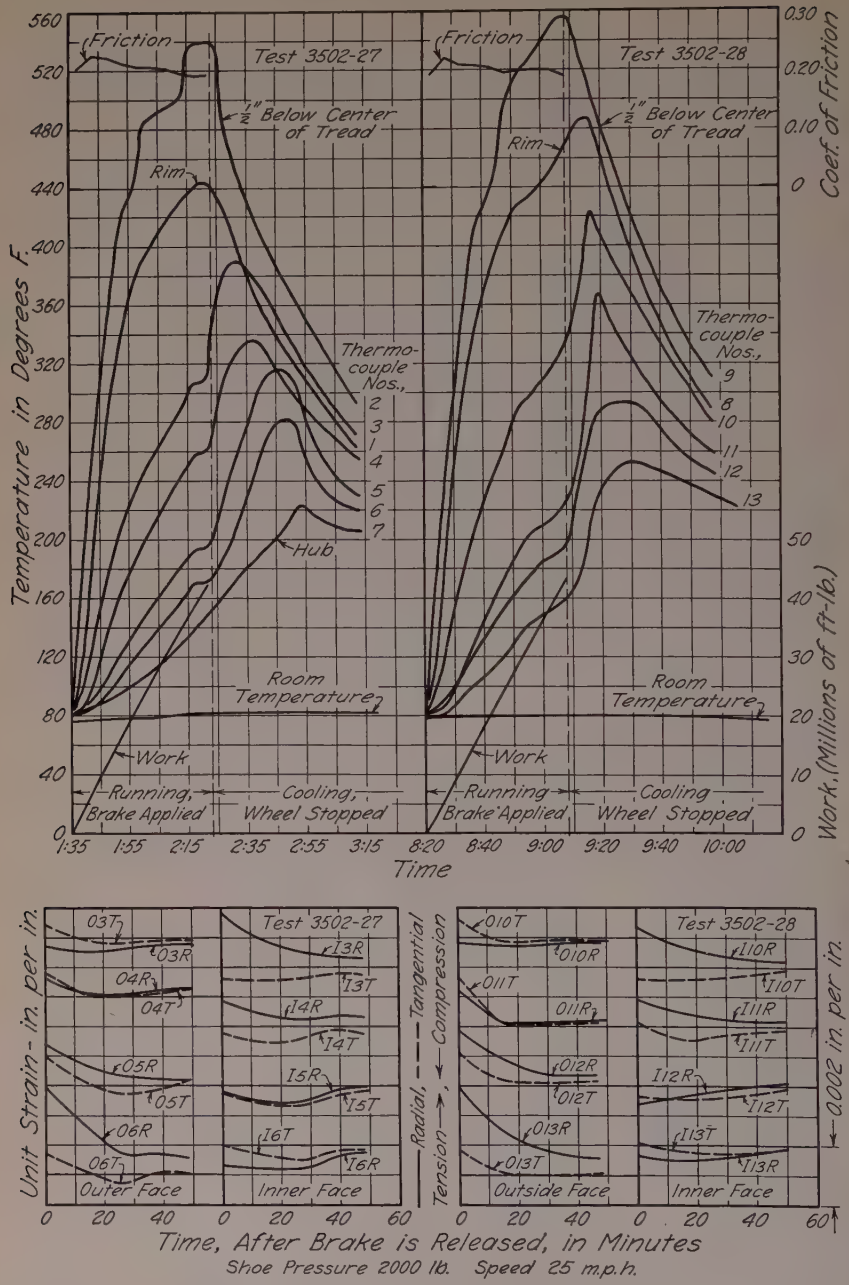


FIG. 16. RESULTS OF TESTS 3502-27 AND 3502-28

For a detailed explanation of these curves see pages 36, 37, and 45.

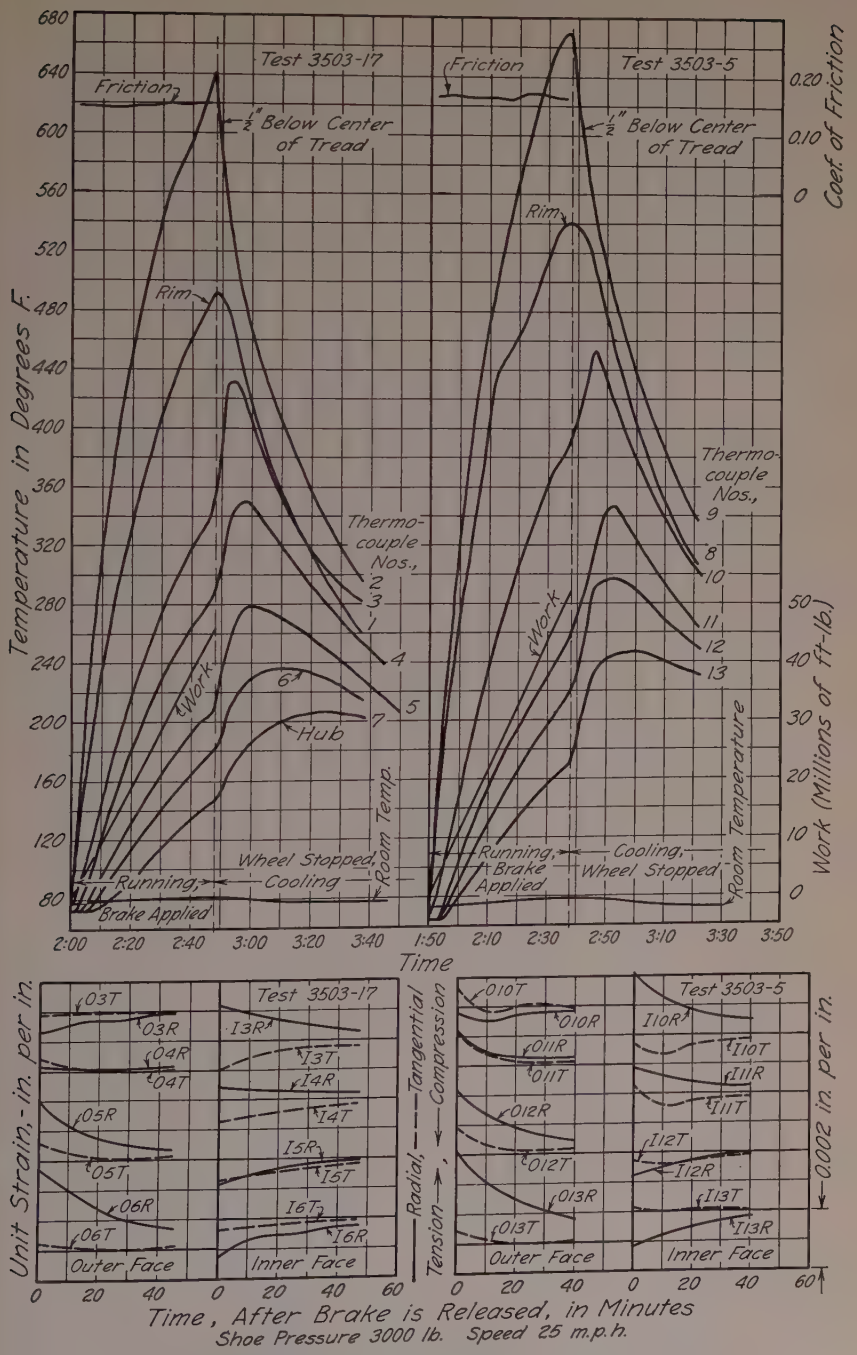


FIG. 17. RESULTS OF TESTS 3503-5 AND 3503-17

For a detailed explanation of these curves see pages 36, 37, and 45.

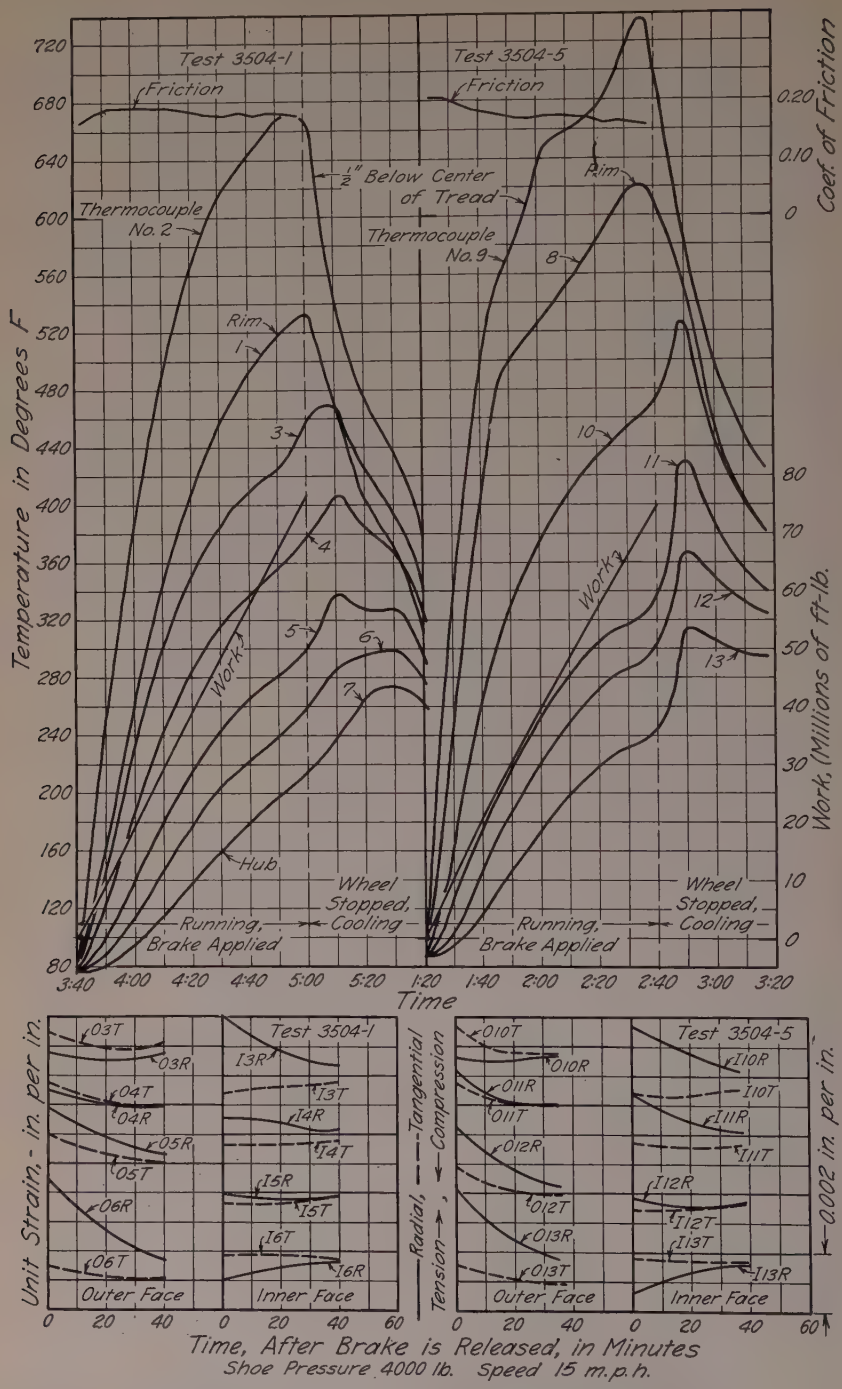


FIG. 18. RESULTS OF TESTS 3504-1 AND 3504-5

For a detailed explanation of these curves see pages 36, 37, and 45.

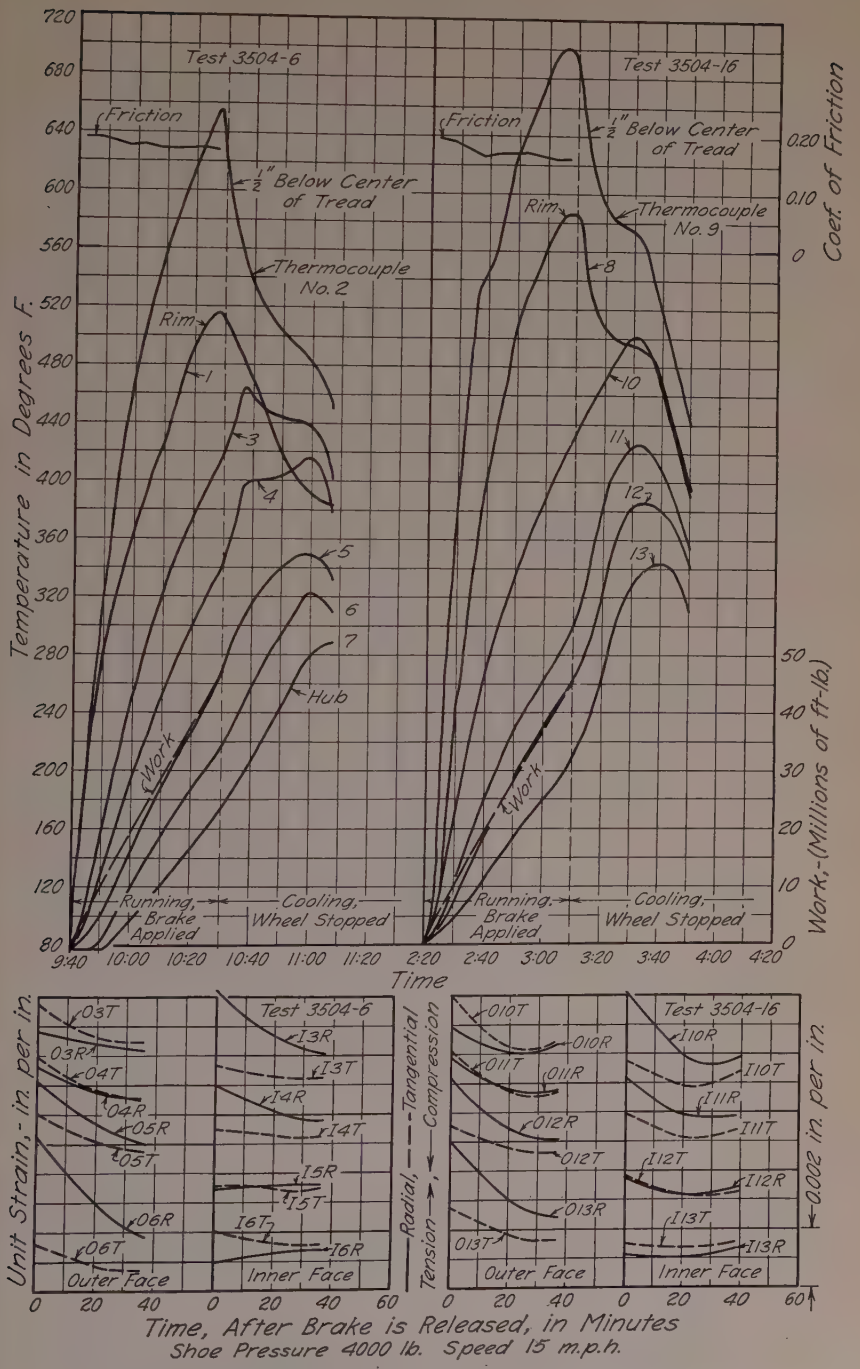


FIG. 19. RESULTS OF TESTS 3504-6 AND 3504-16

For a detailed explanation of these curves see pages 36, 37, and 45.

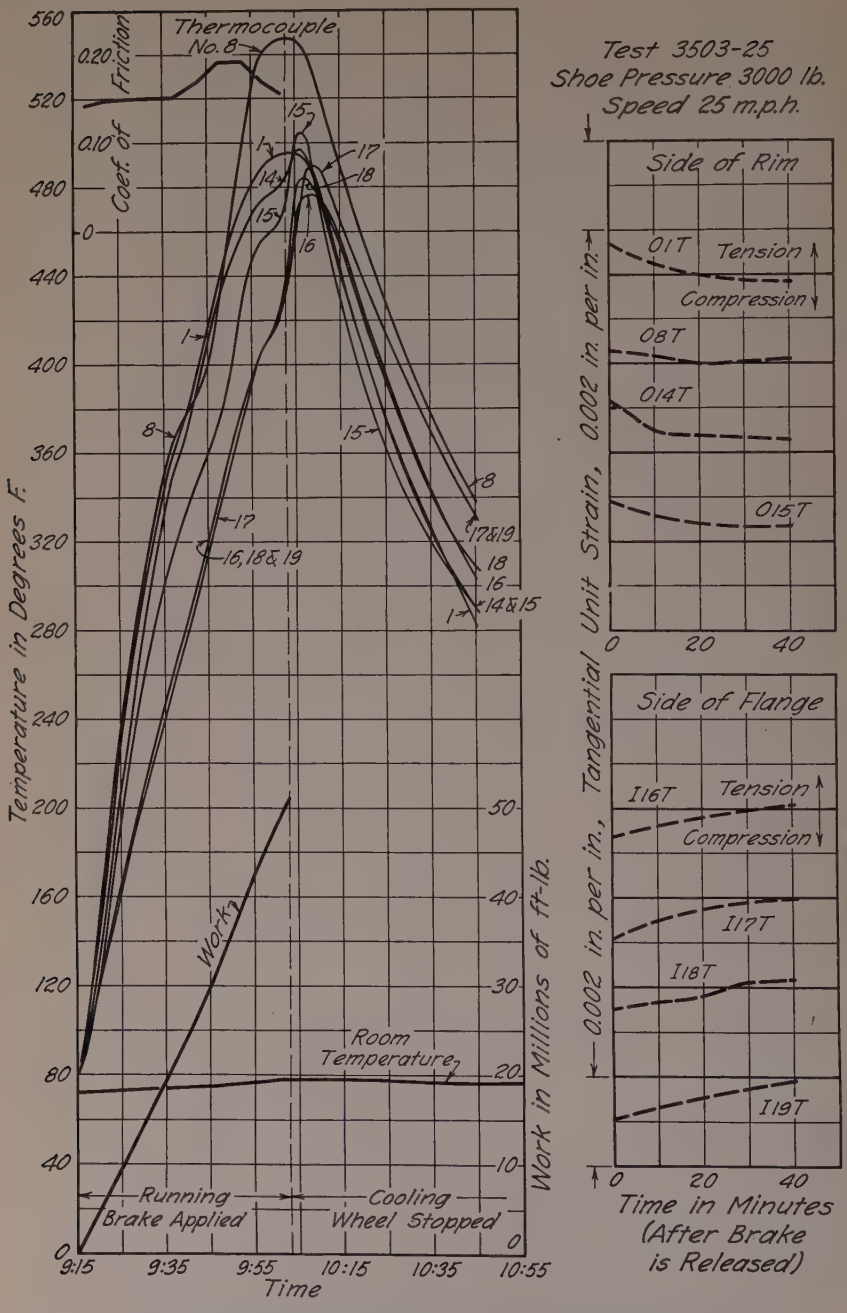


FIG. 20. TEMPERATURE, WORK, FRICTION, AND TANGENTIAL UNIT STRAIN DEVELOPED IN RIM OF WHEEL NO. 1 DURING TEST 3503-25

For a detailed explanation of these curves see pages 36, 37, and 45.

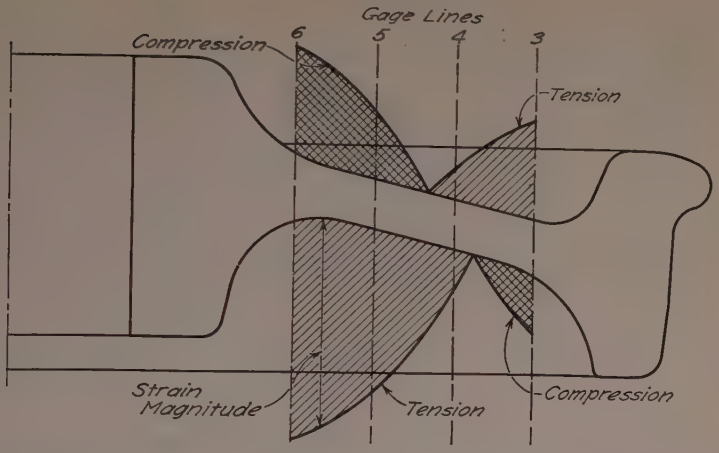


FIG. 21. NATURE, LOCATION, AND MAGNITUDE OF RADIAL SURFACE STRAINS INDUCED IN WHEEL NO. 1 DURING TEST 3503-17, WHICH WAS RUN AT 25 MILES PER HOUR WITH SHOE APPLIED AT 3000 POUNDS PRESSURE FOR 48 MINUTES

part to its expansion under the increase in temperature. To find the net elongation due to the tension alone, the total measured deformation must be diminished by the expansion due to the rise in temperature. This adjustment entails a knowledge of the thermal expansion of the wheel material, which, in this instance, is provided by the curve shown in Fig. 23 in the Appendix. The net deformation, thus determined, may be converted into stress by means of the stress-strain curves of Fig. 24. Neglecting the effects of combined stresses,* the maximum stress found in this investigation was a radial tension of 23 300 pounds per square inch, which corresponds to the maximum strain of 0.0043 inches per inch referred to, and which occurred in test No. 3504-6.

12. *Supplementary Temperature Determinations.*—Early in the investigation it was observed that upon stopping the wheel after a brake application, the temperature on the tread and near the rim decreased rapidly; whereas temperatures of the plate of the wheel near the hub began to increase, and continued to do so at an accelerated rate. The explanation for this was sought in the assumption that the rate of heat transfer from the wheel plate must have been considerably less when quiet than when revolving on the machine. In order to check this assumption, four tests were made, during which

*For explanation of the effects of combined stresses, see University of Illinois Engineering Experiment Station Bulletin 294, which is referred to in Chapter I of this bulletin.

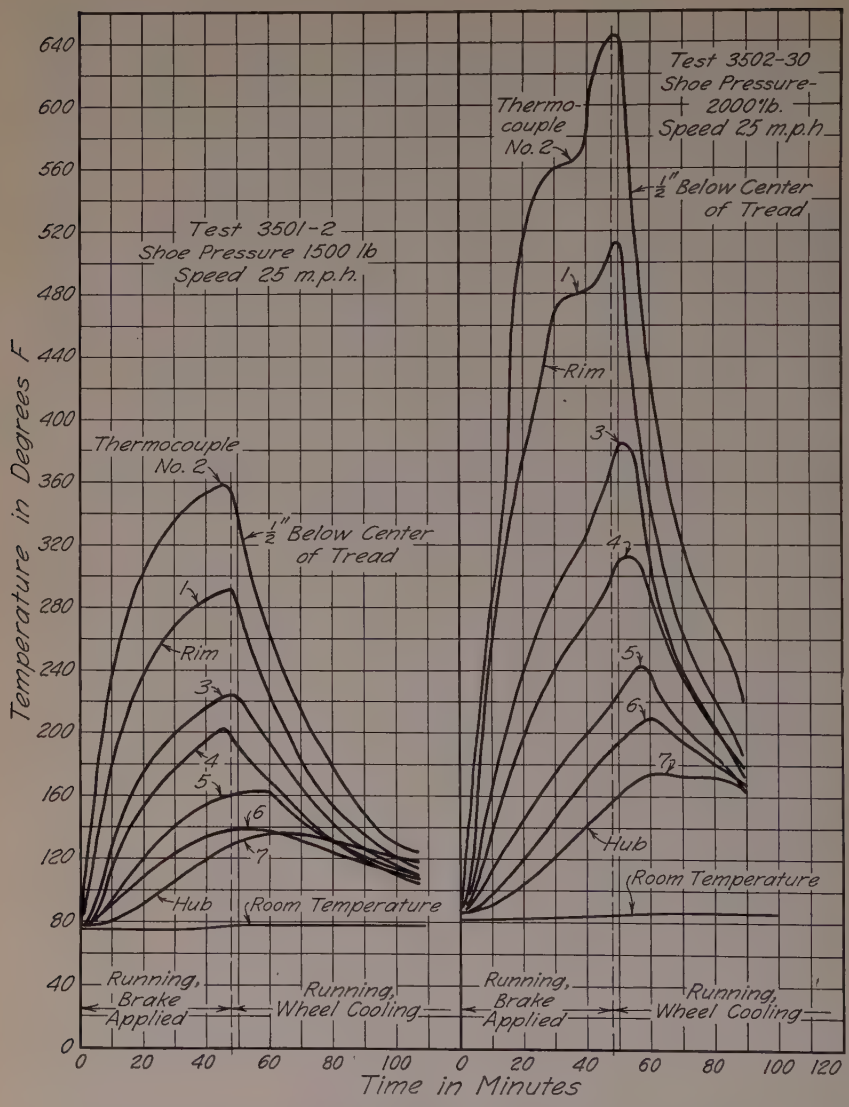


FIG. 22. TEMPERATURE OF THERMOCOUPLES NOS. 1 TO 7 FOR TESTS 3501-2 AND 3502-30, WHEEL RUNNING AT 25 MILES PER HOUR WHILE COOLING

For a detailed explanation of these curves see pages 36, 37, and 45.

the wheel was kept running after the brake was released, and temperatures were measured on the running wheel. The results of two of these tests are shown in Fig. 22. In both tests the wheel was run at 25 miles per hour during both the application and the cooling periods. The shoe pressure in one test was 1500 pounds, in the other, 2000 pounds. In this figure it may be observed that while the temperature of thermocouple No. 7, located near the hub, continued to increase after the release of the brake, this increase was at a rate less than that which prevailed while the brake was still applied; and it ceased about 12 or 15 minutes after the release.

V. Summary and Conclusions

The main purpose of the tests was to determine the resistance of the treads of chilled iron car wheels to heat checking and cracking under long-continued brake applications. A secondary purpose was to find the strains produced throughout one of the wheels under such applications.

13. *Tread Endurance.*—Six wheels were tested; No. 1, at shoe pressures of 1000, 1500, 2000, 3000, and 4000 pounds; Nos. 2, 3, 5, 6, and 7, at 3000 pounds only. Wheel No. 1 was subjected to 30 applications at each of the five pressures—for the first four, at a speed of 25 miles per hour; for the last, at 15 miles per hour. With two exceptions, each application lasted long enough to produce a travel of the wheel tread equivalent to a 20-mile run on the road. The tests of the other five wheels were all made at 25 miles per hour and their duration was 48 minutes, which also produced a tread travel equivalent to 20 miles. Upon the conclusion of the tests, wheels Nos. 1, 2, 3, 5, 6, and 7 had completed, under brake application, equivalent mileages of 2985, 600, 600, 400, 400, and 400 miles, respectively.

Pressures of 1000, 1500, and 2000 pounds did not damage the tread of wheel No. 1 to any considerable extent; only a few heat checks and small cracks having developed during the tests at those pressures. The tests at 3000 pounds shoe pressure, on the other hand, damaged all six wheels, developing in their treads numerous checks and cracks, many of the latter being longer than 2¾ inches, which is the current rejection limit. The pressure of 4000 pounds, applied to wheel No. 1, caused additional damage to its tread. No comby spots or shell-outs developed on any of the wheels during the entire investigation. These results are illustrated and discussed in detail in Section 10 of Chapter IV.

14. *Strains Developed.*—Strains and temperatures were measured on wheel No. 1 only. They were determined under all the combinations of shoe pressure and speed to which this wheel was subjected. The most important strain set up under the various long-continued brake applications is a radial tensile strain on the outer face of the plate, near the hub of the wheel. This strain was not severe at the lower shoe pressures; but it increased rapidly with the pressure. The maximum strain occurred during tests at 4000 pounds shoe pressure. Neglecting the effect of combined stresses, this strain was equivalent to a stress of 23 300 pounds per square inch. The strains and temperatures produced during the investigation are fully discussed in Section 11 of Chapter IV.

APPENDIX

As stated in Chapter IV, in order to convert the measured strains in wheel No. 1 to stresses, it was necessary to determine for the wheel material its rate of thermal expansion, and also its stress–strain relations.

For the determination of the rate of expansion of the material with increasing temperature, specimens were taken from the plate of the wheel. They were right circular cones, approximately ⅛ of an inch in diameter and ⅛ of an inch high. Their expansion was determined, by means of an interferometer, through a temperature range of 80 to 700 deg. F. Throughout this range the rate of heating was two degrees per minute. The results are presented in the curve shown in Fig. 23. As stated in the Introduction, this work was done by Mr. C. L. Thompson, of the Department of Ceramics.

To find the relations between strain and stress, both tension and compression tests were made on material cut from the plate of the wheel—three for the tension tests, and two for the compression tests. The tension specimens were standard half-inch test pieces. The long axis of specimen No. 1 had lain in the wheel in a "tangential" di-

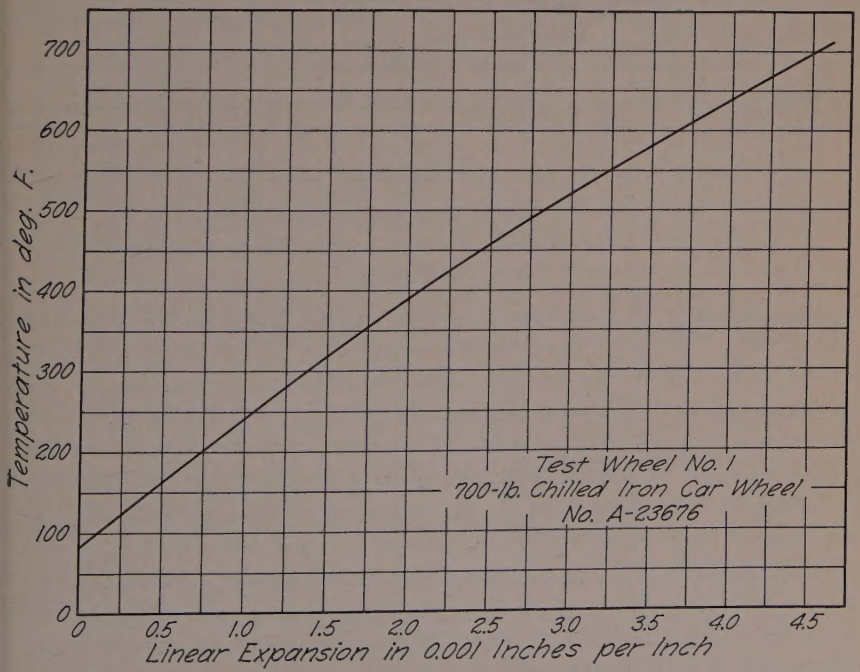


Fig. 23. Thermal Expansion of Specimens Cut From Wheel No. 1

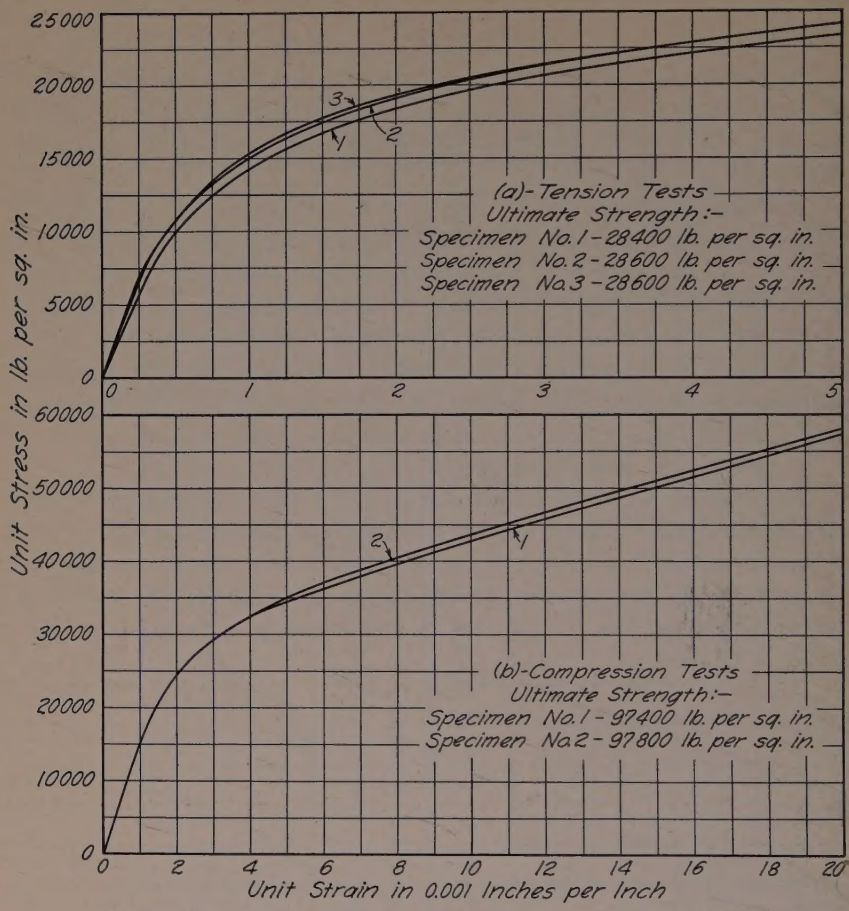


FIG. 24. STRESS–STRAIN DIAGRAMS FOR TENSION AND COMPRESSION TESTS, WHEEL NO. 1

rection; whereas the long axes of specimens Nos. 2 and 3 had lain along wheel radii. The compression specimens were cylinders one inch in diameter and three inches long. The long axis of each of these two specimens had lain along a radius of the wheel-plate. The tension tests were made on a 100 000-pound Amsler testing machine, and the strains were measured by means of an Olsen extensometer. For the compression tests a 300 000-pound Olsen testing machine and a Moore extensometer were employed. Both series of tests were carried out at room temperature. The stress–strain relations thus determined, together with the ultimate strength of the material, are given in Fig. 24. The upper curves apply when the material is in tension; the lower, when it is in compression. This work was done by Mr. R. L. BROWN, of the Department of Theoretical and Applied Mechanics.

RECENT PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION†

Bulletin No. 264. The Strength of Screw Threads under Repeated Tension, by Herbert F. Moore and Proctor E. Henwood. 1934. *Twenty-five cents.*

Bulletin No. 265. Application of Model Tests to the Determination of Losses Resulting from the Transmission of Air Around a Mine Shaft-Bottom Bend, by Cloyde M. Smith. 1934. *Thirty cents.*

Circular No. 23. Repeated-Stress (Fatigue) Testing Machines Used in the Materials Testing Laboratory of the University of Illinois, by Herbert F. Moore and Glen N. Krouse. 1934. *Forty cents.*

Bulletin No. 266. Investigation of Warm-Air Furnaces and Heating Systems, Part VI, by Alonzo P. Kratz, and Seichi Konzo. 1934. *One dollar.*

Bulletin No. 267. An Investigation of Reinforced Concrete Columns, by Frank E. Richart and Rex L. Brown. 1934. *One dollar.*

Bulletin No. 268. The Mechanical Aeration of Sewage by Sheffield Paddles and by an Aspirator, by Harold E. Babbitt. 1934. *Sixty cents.*

Bulletin No. 269. Laboratory Tests of Three-Span Reinforced Concrete Arch Ribs on Slender Piers, by Wilbur M. Wilson and Ralph W. Kluge. 1934. *One dollar.*

Bulletin No. 270. Laboratory Tests of Three-Span Reinforced Concrete Arch Bridges with Decks on Slender Piers, by Wilbur M. Wilson and Ralph W. Kluge. 1934. *One dollar.*

Bulletin No. 271. Determination of Mean Specific Heats at High Temperatures of Some Commercial Glasses, by Cullen W. Parmelee and Alfred E. Badger. 1934. *Thirty cents.*

Bulletin No. 272. The Creep and Fracture of Lead and Lead Alloys, by Herbert F. Moore, Bernard B. Betty, and Curtis W. Dollins. 1934. *Fifty cents.*

Bulletin No. 273. Mechanical-Electrical Stress Studies of Porcelain Insulator Bodies, by Cullen W. Parmelee and John O. Kraehenbuehl. 1935. *Seventy-five cents.*

Bulletin No. 274. A Supplementary Study of the Locomotive Front End by Means of Tests on a Front-End Model, by Everett G. Young. 1935. *Fifty cents.*

Bulletin No. 275. Effect of Time Yield in Concrete upon Deformation Stresses in a Reinforced Concrete Arch Bridge, by Wilbur M. Wilson and Ralph W. Kluge. 1935. *Forty cents.*

Bulletin No. 276. Stress Concentration at Fillets, Holes, and Keyways as Found by the Plaster-Model Method, by Fred B. Seely and Thomas J. Dolan. 1935. *Forty cents.*

Bulletin No. 277. The Strength of Monolithic Concrete Walls, by Frank E. Richart and Nathan M. Newmark. 1935. *Forty cents.*

Bulletin No. 278. Oscillations Due to Corona Discharges on Wires Subjected to Alternating Potentials, by J. Tykocinski Tykociner, Raymond E. Tarpley, and Ellery B. Paine. 1935. *Sixty cents.*

Bulletin No. 279. The Resistance of Mine Timbers to the Flow of Air, as Determined by Models, by Cloyde M. Smith. 1935. *Sixty-five cents.*

Bulletin No. 280. The Effect of Residual Longitudinal Stresses upon the Load-carrying Capacity of Steel Columns, by Wilbur M. Wilson and Rex L. Brown. 1935. *Forty cents.*

Circular No. 24. Simplified Computation of Vertical Pressures in Elastic Foundations, by Nathan M. Newmark. 1935. *Twenty-five cents.*

Reprint No. 3. Chemical Engineering Problems, by Donald B. Keyes. 1935. *Fifteen cents.*

Reprint No. 4. Progress Report of the Joint Investigation of Fissures in Railroad Rails, by Herbert F. Moore. 1935. *None available.*

Circular No. 25. Papers Presented at the Twenty-Second Annual Conference on Highway Engineering, Held at the University of Illinois, Feb. 21 and 22, 1935. 1936. *Fifty cents.*

Reprint No. 5. Essentials of Air Conditioning, by Maurice K. Fahnestock. 1936. *Fifteen cents.*

Bulletin No. 281. An Investigation of the Durability of Molding Sands, by Carl H. Casberg and Carl E. Schubert. 1936. *Sixty cents.*

†Copies of the complete list of publications can be obtained without charge by addressing the Engineering Experiment Station, Urbana, Ill.

Bulletin No. 282. The Cause and Prevention of Steam Turbine Blade Deposits, by Frederick G. Straub. 1936. *Fifty-five cents.*

Bulletin No. 283. A Study of the Reactions of Various Inorganic and Organic Salts in Preventing Scale in Steam Boilers, by Frederick G. Straub. 1936. *One dollar.*

Bulletin No. 284. Oxidation and Loss of Weight of Clay Bodies During Firing, by William R. Morgan. 1936. *Fifty cents.*

Bulletin No. 285. Possible Recovery of Coal from Waste at Illinois Mines, by Cloyde M. Smith and David R. Mitchell. 1936. *Fifty-five cents.*

Bulletin No. 286. Analysis of Flow in Networks of Conduits or Conductors, by Hardy Cross. 1936. *Forty cents.*

Circular No. 26. Papers Presented at the First Annual Conference on Air Conditioning, Held at the University of Illinois, May 4 and 5, 1936. *Fifty cents.*

Reprint No. 6. Electro-Organic Chemical Preparations, by S. Swann, Jr. 1936. *Thirty-five cents.*

Reprint No. 7. Papers Presented at the Second Annual Short Course in Coal Utilization, Held at the University of Illinois, June 11, 12, and 13, 1935. 1936. *None available.*

Bulletin No. 287. The Biologic Digestion of Garbage with Sewage Sludge, by Harold E. Babbitt, Benn J. Leland, and Fenner H. Whitley, Jr. 1936. *One dollar.*

Reprint No. 8. Second Progress Report of the Joint Investigation of Fissures in Railroad Rails, by Herbert F. Moore. 1936. *Fifteen cents.*

Reprint No. 9. Correlation Between Metallography and Mechanical Testing, by Herbert F. Moore. 1936. *None available.*

Circular No. 27. Papers Presented at the Twenty-Third Annual Conference on Highway Engineering, Held at the University of Illinois, Feb. 26-28, 1936. 1936. *Fifty cents.*

Bulletin No. 288. An Investigation of Relative Stresses in Solid Spur Gears by the Photoelastic Method, by Paul H. Black. 1936. *Forty cents.*

Bulletin No. 289. The Use of an Elbow in a Pipe Line for Determining the Rate of Flow in the Pipe, by Wallace M. Lansford. 1936. *Forty cents.*

Bulletin No. 290. Investigation of Summer Cooling in the Warm-Air Heating Research Residence, by Alonzo P. Kratz, Maurice K. Fahnestock, and Seichi Konzo. 1937. *One dollar.*

Bulletin No. 291. Flexural Vibrations of Piezoelectric Quartz Bars and Plates, by J. Tykocinski Tykociner and Marion W. Woodruff. 1937. *Forty-five cents.*

Reprint No. 10. Heat Transfer in Evaporation and Condensation, by Max Jakob. 1937. *Thirty-five cents.*

**Circular No. 28.* An Investigation of Student Study Lighting, by John O. Kraehenbuehl. 1937. *Forty cents.*

**Circular No. 29.* Problems in Building Illumination, by John O. Kraehenbuehl. 1937. *Thirty-five cents.*

**Bulletin No. 292.* Tests of Steel Columns; Thin Cylindrical Shells; Laced Channels; Angles, by Wilbur M. Wilson. 1937. *Fifty cents.*

**Bulletin No. 293.* The Combined Effect of Corrosion and Stress Concentration at Holes and Fillets in Steel Specimens Subjected to Reversed Torsional Stresses, by Thomas J. Dolan. 1937. *Fifty cents.*

**Bulletin No. 294.* Tests of Strength Properties of Chilled Car Wheels, by Frank E. Richart, Rex L. Brown, and Paul G. Jones. 1937. *Eighty-five cents.*

**Bulletin No. 295.* Tests of Thin Hemispherical Shells Subjected to Internal Hydrostatic Pressure, by Wilbur M. Wilson and Joseph Marin. 1937. *Thirty-five cents.*

**Circular No. 30.* Papers Presented at the Twenty-fourth Annual Conference on Highway Engineering, Held at the University of Illinois, March 3-5, 1937. 1937. *Fifty cents.*

**Bulletin No. 296.* Magnitude and Frequency of Floods on Illinois Streams, by George W. Pickels. 1937. *Seventy cents.*

**Bulletin No. 297.* Ventilation Characteristics of Some Illinois Mines, by Cloyde M. Smith. 1937. *Eighty cents.*

**Bulletin No. 298.* Resistance to Heat Checking of Chilled Iron Car Wheels, and Strains Developed Under Long-continued Application of Brake Shoes, by Edward C. Schmidt and Herman J. Schrader. 1937. *Fifty-five cents.*

---

*A limited number of copies of bulletins starred are available for free distribution.